Exploring a sustainable final frontier: Analysing Emerging Space Technologies and the Imperative for Robust Debris Management Frameworks

Authors:

- Darrell Martin-Lawson, Birmingham City Business School, darrell.martin-lawson@mail.bcu.ac.uk. Orcid: 0009-0000-4273-2611 (PhD Candidate)
- Stefania Paladini, Queen Margaret University, spaladini@qmu.ac.uk; Orcid: 0000-0002-1526-3589. (PhD, Professor)
- Krishnendu Saha, Birmingham City Business School, krish.saha@bcu.ac.uk, Orcid: 0000-0002-7836-2728. (PhD, Associate Professor)
- Erez Yerushalmi, Birmingham City Business School, erez.yerushalmi@bcu.ac.uk, Orcid: 0000-0002-9421-9067. (PhD, Associate Professor)

Abstract

The increasing commercialisation and privatisation of outer space, alongside the growing threat posed by space debris, has raised serious concerns about the long-term sustainability of Earth's orbital environments. This paper investigates the current state of space debris management technologies, focusing on patent clustering related to debris prevention, mitigation, and removal strategies. By employing a custom DBSCAN clustering algorithm, this study uncovers key technological trends across space-faring nations, revealing a heavy emphasis on mitigation and removal strategies, while highlighting a notable gap in innovation concerning prevention technologies. The analysis underscores the urgent need for updated legal frameworks, as existing international treaties, including the Outer Space Treaty and Liability Convention, are inadequate in supporting the deployment of emerging debris management technologies. Furthermore, the study advocates for the introduction of economic incentives through policies, such as space taxes and orbital restrictions, to further stimulate innovation in debris prevention and removal. The findings call for a more unified global effort that integrates technological advancements with enforceable policies to secure a sustainable orbital environment for future generations.

Keywords: patent analysis; space sustainability; space debris; dbscan; legal framework; active debris removal

1 Introduction

Since the dawn of the space age, global reliance on space for activities like environmental monitoring, navigation, communication, has steadily grown (Kirchherr et al., 2017; Crane et al., 2020). As humanity's dependence on space-based technologies has expanded, so has the density of objects in Earth's orbit (Bongers and Torres, 2023). The exponential rise in satellites, driven by an increasing number of spacefaring nations and private entities, has led to an increasingly congested orbital environment (Abashidze et al., 2022; Seitzer and Tyson, 2021; Radtke et al., 2017). Emerging industries, like space tourism, promise to bring even more entities into this crowded orbital environment (Spector et al., 2017; Cohen and Spector, 2020). As space becomes more accessible, the risks of collisions and the accumulation of space debris intensify, threatening the sustainability of space operations (Bastida Virgili et al., 2016; Newman and Williamson, 2018). With the advent of large-scale satellite constellations and the possibility of regular commercial space travel, managing space traffic and ensuring the long-term usability of orbital regions has become increasingly urgent. This context underscores the critical need for innovative solutions and robust regulatory frameworks to manage the growing congestion and preserve the space environment for future generations.

The increasing density of objects in low Earth orbit raises the risk of a Kessler event, where cascading debris collisions could render space unusable (Kessler et al., 2010; Drmola and Hubik, 2018). This scenario underscores the urgent need for innovative debris mitigation technologies and a robust regulatory framework. Despite technological advancements, the absence of a fully operational debris removal system and enforceable regulations leaves a significant gap in managing space debris, posing a threat to future missions and the long-term viability of space activities. The financial implications are considerable, with projections estimating debris-related damage could cost USD 66 million annually by 2033 (Martin-Lawson et al., 2024).

The issue of space debris has been widely recognized within the scientific and policy-making communities, leading to various initiatives aimed at understanding and mitigating its impact. Previous studies have explored a range of technological solutions, from passive methods like deorbiting sails to advanced active debris removal (ADR) systems, such as ion beam shepherds, robotic arms, and laser-based deorbiting technologies (Bonnal et al., 2013; Bombardelli and Peláez, 2012; Nishida et al., 2009; Ledkov and Aslanov, 2023; Svotina and Cherkasova, 2023). While these efforts have demonstrated the technical feasibility of debris removal, significant gaps remain, particularly in scaling these technologies and integrating them within a cohesive regulatory framework. Although some nations and private entities are investing in ADR technologies, such as the ClearSpace-1 and Astroscale missions, these initiatives are still in the early stages and not yet widely operational. Moreover, existing legal frameworks, including the Outer Space Treaty and the Liability Convention, are increasingly seen as outdated, lacking the specificity and enforceability needed to address the complexities of modern space activities. This gap between technological advancements and regulatory support underscores the need for comprehensive research that not only advances debris mitigation technologies but also addresses the legal and policy challenges hindering their widespread adoption.

This paper explores the landscape of emerging space technologies by analysing patent data, with a focus on innovations related to space debris management. By examining the patent activity of various countries, this study identifies where efforts are concentrated and how nations prioritize technologies aimed at addressing space debris. Specifically, the paper categorizes debris-related patents into prevention, mitigation, and removal, offering a detailed assessment of strategic focuses within each country. This analysis provides new insights into the current state of technological innovation in space debris management and underscores the critical need for stronger regulatory frameworks to drive and support these innovations on a global scale. Ultimately, the findings contribute to the ongoing discourse on space sustainability, highlighting gaps and opportunities for more coordinated international efforts in debris management.

Therefore, the aim of this paper is to analyse global trends in emerging space debris management technologies through patent data, highlighting innovations in prevention, mitigation, and removal, while emphasizing the need for stronger regulatory frameworks to support these advancements. To do this, we employ a custom DBSCAN clustering algorithm to analyse and categorize patents related to space debris management. A distance matrix based on structural and semantic similarities was created to identify clusters of patents focused on prevention, mitigation, and removal, highlighting trends in space debris innovation and emphasizing the need for stronger regulatory frameworks. The study's findings provide crucial insights for guiding policy and investment in space debris management, identifying key technological trends and gaps. The research underscores the need for stronger legal frameworks to support innovation, contributing to both practical debris management strategies and academic understanding of space sustainability.

With this aim in mind, Section **Error! Reference source not found.** discusses the critical role of patents and clustering analysis in driving technological innovation. Section **Error! Reference source not found.**, examines the challenges posed by space debris and the need for updated legal frameworks. Section **Error! Reference source not found.** presents the construction of the clustering algorithm. Section 5 presents our results. Section 6 discusses the current advancements in space debris management technologies, highlighting global trends, challenges, the role of policy pertaining to debris management and suggests directions for future research. Section 7 concludes the paper.

2 Patent Analysis in Driving Innovation

Innovation economics, a field of economics theory, focuses on how innovation and technological progress drive economic and societal advancement (Mohamed et al., 2022). It highlights the importance of developing, adopting, and spreading new technologies for sustained economic development. Patents, especially in high-tech fields like aerospace, are key indicators of technological progress (Benson and Magee, 2015). The aerospace industry is characterized by high entry barriers, significant R&D

investments, and rapid technological change, making patents crucial for maintaining a competitive advantage (Pop et al., 2023). Studies have shown that the aerospace sector, with its high-tech nature, relies heavily on both public and private funding to support innovation, and patents are a key mechanism through which these innovations are protected and commercialised (Sydorenko and Poltavska, 2021; Belz and Giga, 2018).

Moreover, patents facilitate the exchange of information. By disclosing technical details of new inventions, patents contribute to the diffusion of knowledge, allowing other entities and researchers to build upon existing technologies, fostering further innovation (Seymore, 2010; Baruffaldi and Simeth, 2015). In high-tech sectors, the strategic use of patents can also influence the direction of technological development. For instance, companies in the aerospace industry may use patents not only to protect their inventions but also to shape the competitive landscape by securing key technologies and setting industry standards (Pohlmann and Blind, 2014; Holgersson and Granstrand, 2022).

The number of patents filed by a firm, industry, or country often reflects its level of innovative activity (Linares et al., 2019; Pohlmann and Blind, 2014). The Patent Portfolio Model (PPM) is a tool used to assess an organization's technological strength through patent portfolio analysis (Li et al., 2020). This model helps in identifying technological advantages and guiding strategic decisions in R&D investments (Li et al., 2020). Additionally, patents can reveal the direction of technological developments and the emergence of new fields of innovation, making them a valuable resource for policymakers and business leaders (Jaffe and Trajtenberg, 2003; Li et al., 2021a).

Patents also actively drive innovation by securing the economic benefits of technological advancements (Holgersson and Granstrand, 2022). By granting inventors temporary monopolies on their innovations, patents ensure that innovators profit from their inventions (Barash, 1996). This financial security encourages continued investment in innovation, leading to a cycle of technological progress and economic growth. The relationship between patents and innovation is particularly evident in industries that rely heavily on R&D, such as healthcare and aerospace (Huang et al., 2016; Lee et al., 2015).

Moreover, patents contribute to the diffusion of knowledge by requiring the disclosure of technical details about new inventions (Baruffaldi and Simeth, 2015). This disclosure facilitates the diffusion of innovation, allowing other researchers and firms to build upon existing knowledge (Baruffaldi and Simeth, 2015). The strategic use of patents can also influence the allocation of resources within firms and industries. For example, patents can guide firms in identifying and prioritizing key areas for R&D investment (Miyashita et al., 2020).

The space sector relies on patents to protect intellectual property and incentivize the continuous development of technology. This is particularly true in areas critical to space sustainability, such as debris management (Jaffe and Trajtenberg, 2003). The accumulation of debris in Earth's orbit poses a growing threat to both current and future space operations (Allen et al., 2019; Smirnov et al., 2015; Martin-Lawson et al., 2024). Patents related to debris management technologies are critical in addressing these challenges, as they help secure the economic benefits of innovation while promoting the development of solutions to address space debris. For instance, recent studies have highlighted the role of advanced technologies such as autonomous systems, robotics, and AI in integrated debris mitigation strategies (Newman and Williamson, 2018; Heilala, 2023).

Through the analysis of patents, researchers and policymakers can identify emerging technologies that could significantly impact space sustainability. For example, a study on technology trends in New Space missions using a patent analytics approach identified key areas of innovation, including remote sensing, telecommunication systems, and space platforms (Garzaniti et al., 2021). Such analyses can provide valuable insights into the types of technologies that are being prioritized in the debris management and the space sector.

Clustering analysis in patent analytics groups similar patents by characteristics like keywords, classifications, or citations, enabling researchers and policymakers to identify emerging technologies, innovation hotspots, and key areas of focus (Oyelade et al., 2019). For instance, by analysing patent data related to space debris, clustering techniques can reveal new approaches or innovations that are gaining traction within the field. This method has been used effectively to identify technological trends in various sectors, including space technology, where innovations are critical for addressing challenges such as debris management (Ribeiro et al., 2018; Altuntas et al., 2020).

Clustering analysis not only identifies emerging technologies but also highlights areas where technological activity is particularly intense. These hotspots are often suggestive of where future breakthroughs are likely to occur and where investment might be most effectively directed. Such as Garzaniti et al's (2021) aforementioned study on patent analysis on New Space missions. The insights gained from clustering analysis are invaluable for guiding policy and investment decisions. Policymakers can use the results to prioritise funding for research and development in areas identified as emerging or strategically important (Ribeiro et al., 2018). Additionally, investors can use these insights to identify promising technologies and allocate resources more effectively. For example, patent clustering has been used to explore nuclear waste management technologies, revealing regional differences and guiding decisions on where to focus technological development efforts (Suh et al., 2020).

The identification of technological trends through patent clustering analysis is crucial for understanding the current state and future direction of space innovation, particularly in addressing the growing challenge of space debris. However, recognising these trends is only one part of the equation. To ensure that these innovations are effectively implemented and contribute to sustainable space activities, they must be supported by robust legal and regulatory frameworks. The absence of appropriate governance can lead to fragmented efforts, where technological advancements fail to achieve their full potential due to regulatory gaps or inconsistencies (Biermann et al., 2009). In Section **Error! Reference source not found.**, we will explore the current legal and regulatory frameworks governing space debris and assess their effectiveness in addressing the challenges posed by the increasing density of objects in Earth's orbit.

3 Legal Frameworks in Addressing Space Debris

Space debris has increasingly become a central issue in discussions of space sustainability which the United Nations' Committee on the Peaceful Uses of Outer Space (UN COPUOS) defines as: *'the ability to maintain the conduct of space activities indefinitely into the future in a manner that realises the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations*' (UN COPUOS, 2018). Over the past several decades, the accumulation of defunct satellites, spent rocket stages, and fragments from collisions has increasingly cluttered Earth's orbital environment (Svotina and Cherkasova, 2023; Liou and Johnson, 2006). As the number of active satellites grows, the risks associated with space debris continue to escalate.

The problem of space debris not only poses a direct threat to operational spacecraft through collisions but also intensifies the long-term risks of space operations by increasing the likelihood of cascading collisions, a scenario known as a Kessler Syndrome (Drmola and Hubik, 2018). This phenomenon, first proposed by NASA scientist Donald J. Kessler in 1978, described a situation where the density of objects in low Earth orbit (LEO) is high enough that collisions between objects cause a chain reaction, increasing the number of debris fragments and potentially rendering parts of space unusable (Kessler, 2000). According to Martin-Lawson et al (2024), using their probability-based empirical model to project the growth trajectory of objects in space, we could cross the 'critical density' threshold in the upcoming years if no debris clean up actions take place.

The challenge of space debris management is compounded by the fact that Earth's orbital space can be considered as an Areas Beyond National Jurisdiction (ABNJ) (Martin-Lawson et al., 2024). As more nations and private entities gain access to space, the need for coordinated international efforts to mitigate debris becomes increasingly critical. Without such coordination, the risk of unmanageable debris levels could jeopardize not only individual missions but also the broader goals of space exploration and utilisation (Usovik, 2023; Smirnov et al., 2015).

Space debris is now a key issue in space sustainability, leading to international policies and regulations to address its risks. The Outer Space Treaty (OST) of 1967, is seen as one of the core treaties pertaining to space law, which forms the foundational legal framework for all activities in outer space. The OST emphasizes that outer space shall be free for exploration and use by all nations, and places importance on the sustainable use of the outer space (UNOOSA, 1967).

The OST is complemented by treaties such as the Liability Convention (UNOOSA, 1971), which holds states liable for damage caused by their space objects, and the Registration Convention (1975) (UNOOSA, 1975), which requires the registration of space objects with the UN. These treaties establish a legal obligation for states to manage their space objects, but they fall short in providing specific guidelines for the management of space debris. The Inter-Agency Space Debris Coordination Committee (IADC), established in 1993, developed voluntary guidelines recommending best practices for limiting debris generation, including the deorbiting of LEO satellites within 25 years of mission completion to reduce collision risks (IADC, 2007; Hakima and Emami, 2018). However, these guidelines lack enforceability and are often dependent on the voluntary compliance of spacefaring entities, which has led to varying levels of adherence to the guidelines (Tian, 2019; Newman and Williamson, 2018).

Added to this, there is an ongoing need to modernize these frameworks to address new challenges posed by the rapid commercialization of space, particularly large satellite constellations like Starlink (Abashidze et al., 2022; Seitzer and Tyson, 2021). The growing number of objects in space, coupled with the lack of a binding international regulatory framework, underscores the urgency of developing more robust and enforceable global governance mechanisms for space debris management (Martin-Lawson et al., 2024).

The recent surge in regulatory activities, such as the United States' Executive Order 13914 (Trump, 2020), highlights the complexities of establishing a cohesive international legal framework for outer space. This order, which rejects the notion of outer space as a global common, marks a significant shift in the U.S. approach to space governance and sets a precedent that could potentially undermine international efforts to manage space debris sustainably (Martin-Lawson et al., 2024).

The legal frameworks governing space activities have not kept up with the technological advancements of the space sector (Freeland, 2020). The aforementioned treaties, the OST and the Liability Convention, are increasingly seen as outdated for addressing the complexities of contemporary space activities (Newman and Williamson, 2018). One limitations of the existing legal frameworks are their lack of specificity regarding the management of space debris. The OST provides broad principles but does not offer detailed regulations on space debris management. This gap is problematic given the increasing density of objects in Earth's orbit, which raises the risk of a Kessler event (Bastida Virgili et al., 2016; Kessler and Cour-Palais, 1978). The issue of ownership and responsibility further complicates the legal landscape. Under the OST, states retain ownership over objects they launch into space, even after objects become non-functional. This has created legal challenges, as the responsibility for debris mitigation lies primarily with states rather than the private entities that operate many of the satellites, making it difficult for private operators to take action to remove debris (Li, 2015).

Moreover, the Liability Convention is considered inadequate for the current space environment. The convention holds states liable for damage caused by their space objects but does not effectively address the complexities of collisions involving space debris or the challenges of attributing responsibility in the case of multi-party involvement (Dennerley, 2018). As a result, there may be little incentive for states or private operators to invest in debris mitigation technologies, intensifying the problem of space debris accumulation.

To manage space debris effectively, the international legal framework needs significant updates and reforms. These should include clearer definitions of responsibilities for debris mitigation, mechanisms for international cooperation in ADR, and the establishment of a dedicated regulatory body or framework specific to space debris management. Without such reforms, the legal ambiguities and gaps will continue to hinder efforts to achieve a sustainable and safe orbital environment.

In their papers, (Paladini and Saha, 2023) (add paper 2 as well) highlight that technology is a limiting factor in the sustainable development of space tourism. The challenge of space debris management, like space tourism, is constrained by the pace and scope of technological advancements, with both areas heavily relying on cutting-edge technologies (Murtaza et al., 2020). These technological advancements are critical for addressing the growing problem of space debris, but their successful implementation hinge on the adequacy of existing legal and policy frameworks.

Recent advancements in space debris management include innovations such as the ion beam removal system, laser-based debris deorbiting, and active debris capture technologies (Garzaniti et al., 2021; Ledkov and Aslanov, 2023; Svotina and Cherkasova, 2023; Zhang et al., 2023; Ribeiro et al., 2018). Patent clustering has revealed a surge in technologies designed to tackle space debris, from robotic arms for capturing defunct satellites to systems for tracking and avoiding debris collisions (Ribeiro et al., 2018). These innovations aim to mitigate the environmental impact of space debris.

Despite the promising developments in debris management, the current legal and regulatory frameworks are insufficient to support their widespread implementation (Freeland, 2020). To bridge the gap between technological innovation and effective debris management, there is a need for robust legal and policy support. Technological solutions for debris management require not only development and deployment but also supportive regulatory frameworks that facilitate their integration into space operations (Jakhu et al., 2017). This includes establishing clear responsibilities for debris mitigation, creating incentives for private operators to adopt new technologies, and ensuring international cooperation to address the global nature of space debris (Martin-Lawson et al., 2024; Bastida Virgili et al., 2016). To align technological advancements with regulatory needs, several reforms are necessary:

Enhanced Regulations: Develop more detailed and binding regulations specific to space debris management, including standards for debris mitigation and removal.

International Cooperation: Foster international agreements that promote collaborative efforts in debris management and create mechanisms for shared responsibility and enforcement.

Incentive Structures: Implement policies that encourage the adoption of innovative debris management technologies through financial incentives, grants, and support for R&D.

Addressing the regulatory gaps and integrating new technologies into a cohesive management strategy will be crucial for ensuring the long-term sustainability of space activities.

The identification of technological trends and the analysis of legal frameworks provide crucial insights into addressing the growing challenge of space debris. However, these efforts must be integrated into a coordinated approach that combines technological innovation with updated legal frameworks to manage space debris effectively. Moving forward, it is essential to pursue a holistic strategy that includes both the development of advanced debris mitigation technologies and the modernisation of international space law. This dual approach will help ensure that the space environment remains safe and accessible for future generations.

4 Constructing the Clustering Algorithm

We set up our custom clustering algorithm using the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) aimed at creating a cluster visualisation (Hui and Liu, 2020; Ester et al., 1996). This approach was preferred to other clustering algorithms (e.g., K-means, Hierarchical, Grid-based, Model-based Benabdellah et al., 2019).

The classification of patents into separate distinct clusters was the aim when searching for an effective way to uncover distinct themes within the data. The generation of a clustering network using computational power can be with several techniques as mentioned above.

The DBSCAN is a popular clustering technique which, according to (Tran et al., 2013), belongs to the third category of clustering methods, density-based clustering, which assumes that a cluster is identified by dense regions in the data. Aside from density-based there are other forms of clustering techniques such as partitioning (K-means), hierarchical (agglomerative clustering), grid-based (STING) and model-based (MCLUST) (Madhulatha, 2012).

Partitioning-based clustering is a popular technique used to divide a dataset into distinct cluster, such that data points within a cluster are more similar to each other than to those in other clusters. One of the most popular methods used within this category is K-means clustering (Madhulatha, 2012). K-means clustering is a centroid-based algorithm that partitions the data into K distinct clusters. The algorithm works by iteratively assigning each data point to the nearest cluster centre (centroid) and then recalculating the centroids based on the mean of all points in the cluster. This process continues until the assignments no longer change, and the clusters have stabilized (Jain et al., 1999). K-means clustering is particularly effective in scenarios where the number of clusters (K) is known, and the data is well-suited to spherical clusters. It is widely used in various fields, including image compression, text document clustering, and customer segmentation in marketing (Fahim et al., 2008; Kalam and Manikandan, 2011; Hornik et al., 2012). Though very popular, K-means has some limitations, such as sensitivity to the initial placement of centroids and difficulty in handling clusters of varying sizes or densities (Rahim and Ahmed, 2017; Melnykov and Zhu, 2019; Aliwy and Aljanabi, 2016).

Hierarchical clustering is another widely used technique for dividing a dataset into clusters, and it operates by building a hierarchy of clusters. Among the different approaches to hierarchical clustering, agglomerative clustering is particularly popular (Madhulatha, 2012). In agglomerative clustering, the process begins by treating each data point as its own cluster. These individual clusters are then iteratively merged based on their similarity until a single cluster encompassing all data points is formed or until a desired number of clusters is reached (Murtagh and Contreras, 2012). Agglomerative clustering is typically represented through a dendrogram, a tree-like diagram that illustrates the nested structure of the clusters. At each step, the two closest clusters are combined to form a new, larger cluster. The closeness of clusters can be measured in various ways, including single linkage (the minimum distance between points in the clusters), complete linkage (the maximum distance between points), or average linkage (the average distance between all pairs of points in the clusters (Tokuda et al., 2022). The process continues until all data points are grouped into a single cluster or the desired number of clusters is obtained. Hierarchical clustering is widely applied in fields such as bioinformatics, where it is used to analyse gene expression data, helping to identify groups of genes with similar expression patterns (Jothi et al., 2021). It is also employed in document clustering to organise large collections of text documents based on their content and in social network analysis to detect community structures within networks, as well as in graph mining (Newman et al., 2003), human brain analyses (Boly et al., 2012; Schoffelen et al., 2017), environmental assessment (Dugan et al., 2017), and incidence relation identification (Xie et al., 2020; Fortunato, 2010). However, hierarchical clustering has some limitations. The method is computationally intensive, especially for large datasets, because the algorithm must compute and update the distances between all pairs of clusters at each step (Xie et al., 2020). Additionally, once a merge is made, it cannot be undone, which can lead to suboptimal clustering results if an incorrect merge occurs early in the process. Furthermore, the method is sensitive to noise and outliers, which can distort the resulting cluster hierarchy (Fortunato, 2010; Murtagh and Contreras, 2012).

Grid-based clustering is another clustering technique employed to partition a dataset into a grid structure, dividing the data space into a finite number of cells or grids based on a defined resolution (Madhulatha, 2012). A prominent method within this category is STING (Statistical Information Grid), which is designed for efficient processing of large spatial databases (Oyelade et al., 2019). The STING algorithm operates by summarizing the statistical properties of the data within each grid cell, such as the mean, variance, and density. These summaries are then used to identify clusters at various levels of resolution (Oyelade et al., 2019). STING works by constructing a hierarchical grid structure where the data space is divided into smaller rectangular cells at different levels of granularity. At the finest level, the data is split into the smallest cells, and statistical information is computed for each. Higher-level cells are formed by merging these lower-level cells, and their statistical properties are aggregated accordingly (Saini and Rani, 2017). Clustering is achieved by traversing this hierarchical structure from the top down, merging cells or identifying clusters based on predefined statistical criteria at each level. This hierarchical approach allows STING to efficiently detect clusters of varying shapes and sizes by adjusting the resolution of the grid (Shah and Nair, 2015). STING has found applications in various fields, notably in geographic information systems (GIS) and spatial data mining, where it is used to uncover spatial patterns and relationships (Arendt et al., 2021). It is particularly effective for analysing large datasets where the spatial distribution of data points must be examined at different levels of detail (Arendt et al., 2021). Additionally, STING is utilized in environmental monitoring to identify regions with similar environmental conditions or to detect areas of interest, such as hotspots of pollution or disease outbreaks (Balka and De Nardo, 2021). However, STING also has its limitations. The algorithm's effectiveness is highly dependent on the grid resolution chosen, which must be carefully selected; an inappropriate resolution can either overlook important clusters or generate misleading results (Tareq et al., 2022; Vani and Hema, 2021). Additionally, STING assumes a uniform distribution of data within each grid cell, an assumption that may not hold in real-world datasets. This can result in inaccuracies, particularly in cases where data distribution is skewed or contains significant outliers (Vani and Hema, 2021).

Model-based clustering is a statistical method that aims to identify clusters by fitting models to a dataset (Madhulatha, 2012). MCLUST, a widely used model-clustering algorithm software package, offers a range of models that cater to different shapes and orientations of clusters in multivariate data (Fraley and Raftery, 2002, 1999). The algorithm works by fitting a mixture of Gaussian distributions to the data using the Expectation-Maximization (EM) algorithm, optimising the fit through the Bayesian Information Criterion (BIC) to determine the optimal number of clusters (Fraley and Raftery, 1999, 2002). MCLUST has been applied across various fields due to its flexibility and effectiveness in handling different types of data. For example, it has been used in the classification of astronomical data, where it helps in identifying and grouping celestial bodies based on their properties (Kang et al., 2019). Additionally, in biomedical research, MCLUST has been used in gene expression analysis, where it assists in grouping genes with similar expression patterns together. (Yeung et al., 2001). Although useful, MCLUST also has certain limitations. One drawback is the assumption that data can be adequately modelled by gaussian distributions, which may not hold true for all datasets (Zhang and Di, 2020). Moreover, the algorithm can be sensitive to the choice of initial parameters which may lead to suboptimal clustering results (Scrucca and Raftery, 2015). Finally, the performance of MCLUST can be compromised by outliers or noise, which can alter the estimation of model parameters and, consequently, impact clustering negatively (Evans et al., 2015).

As mentioned above, DBSCAN is a popular clustering algorithm that identifies clusters based on the density of data points. The DBSCAN defines clusters as areas of high density separated by areas of lower point density, allowing the DBSCAN to identify clusters of arbitrary shapes and effectively manage noise within the data (Ester et al., 1996). According to (Schubert et al., 2017; Gan and Tao, 2015) the DBSCAN works by evaluating the density of points within a specified neighbourhood around each data point, defined by the parameter’s eps (the radius of the neighbourhood) and min_samples (the minimum number of points required to form a dense region). Points that meet these density criteria are classified as core points, while those within the neighbourhood of a core point but not dense enough themselves are considered border points. Points that do not fit either category are labelled as noise. The algorithm groups core and border points into clusters by expanding from each core point, thereby identifying clusters of varying shapes and size. DBSCAN has been widely applied in various fields due to its ability to handle clusters of irregular shapes and manage noise effectively. For example, it has been used in environmental monitoring to detect pollution hotspots, in astronomy to classify celestial bodies, and in marketing to segment customers based on purchasing behaviour, even in noisy datasets (Actkinson and Griffin, 2023; Bastien and Somanah, 2019). Although useful at clustering data, DBSCAN does have limitations. The algorithm's effectiveness is highly dependent on the choice of eps and min_samples parameters, which can be difficult to determine without domain knowledge (Li et al., 2021b). Moreover, DBSCAN can struggle with datasets that have clusters of varying densities, as the algorithm assumes a uniform density threshold throughout the dataset, which can lead to merger of distinct clusters (Fahim, 2022).

DBSCAN was particularly suitable for our research on clustering patent data based on a custom distance matrix for multiple reasons. Patent data often involves complex relationships and varying levels of similarity, making traditional clustering methods like K-means less effective (Zhang et al., 2016). DBSCAN's ability to identify clusters based on actual data structure, without assuming spherical clusters, was crucial. Added to this, unlike partitioning methods, DBSCAN does not require specifying the number of clusters in advance (Ester et al., 1996). Moreover, the algorithm's robustness in handling noise allowed for clearer more relevant clustering of patents themselves, making it an ideal method for clustering our patent dataset (Schubert et al., 2017).

Aside from choosing the clustering algorithm for the data, the language used to implement DBSCAN was also important to consider. Python is a useful programming language for implementing DBSCAN in data analysis due to its extensive libraries, such as Scikit-learn, which facilitate the efficient clustering of complex, high-dimensional data often encountered in patent datasets. Its flexibility and powerful data handling capabilities allow for scalable and reproducible analysis, making it particularly suited for the requirements of patent data clustering (Agapito et al., 2022). This is why the python programming language was used over other languages.

To our knowledge, there is limited academic literature that systematically compiles space-related patents and applies clustering algorithms to identify groups representing emerging technologies, including those focused on debris management. While there is a growing body of work on patent analysis, most studies focus on specific aspects such as network analysis or citation patterns rather than clustering for technological categorisation.

For instance, Chakraborty et al (2020) conduct a comprehensive patent citation network analysis using descriptive statistics and Exponential Random Graph Models (ERGMs) to understand the structural properties of patent networks. Similarly, (Jeon and Suh, 2019) utilize multiple patent network analysis techniques to identify safety technology convergence, providing insights into how various technologies coalesce within patent networks. However, these studies do not employ clustering algorithms like DBSCAN for grouping related patents.

In another relevant study, Pantoja et al (2022) explore graph representation learning for patent network analysis, which, while powerful, focuses more on understanding the relationships within patent networks rather than identifying emergent technological clusters. Lei et al (2019) apply a feature vector space model for patent analytics in the context of IoT, which is somewhat closer to our approach but still lacks the focus on space-related patents and debris management. Lastly, Ribeiro et al (2018) conduct a bibliometric and patent analysis to explore the evolution of space debris mitigation technologies. Although their work is directly relevant to space debris, it primarily centres on policy evolution rather than the clustering of emerging technologies as done in our study. Our work builds on these approaches by integrating clustering algorithms to identify and categorize space-related patents, specifically focusing on debris management technologies, thereby filling a gap in the existing literature.

In a study by Li (2021) the DBSCAN algorithm was employed to evaluate traditional Chinese medicine (TCM) patents. By clustering the TCM patents based on their legal evaluation indices, DBSCAN effectively identified clusters within the dataset, allowing for a detailed analysis of patent law evaluation. The algorithm's ability to manage noise and distinguish between dense and sparse areas in the data led to the creation of a model with an average accuracy of 91.97%, outperforming other domestic models used for similar purposes. Similarly, in the work by Han et al (2019), DBSCAN was applied to clarify inventor names in the USPTO patent database. By clustering inventor records based on semantic fingerprinting, DBSCAN facilitated the accurate identification of unique inventors, even in the presence of noise in the dataset. The results demonstrated that DBSCAN not only improved the precision of inventor name identification but also reduced the computational resources required, making it a powerful tool for patent data analysis.

In the initial phase of our analysis, we conducted exploratory data analysis (EDA) on the patent and debris datasets to uncover patterns and insights that would guide further investigation. This included summarizing the distribution of patents across different International Patent Classification (IPC) codes, analysing trends in patent filings over time, and visualizing the geographic distribution of these filings. For instance, we examined the frequency of IPC codes to identify the most common classifications, tracked the number of patents filed each year to observe temporal trends, and plotted the distribution of patents by country to understand regional innovation activities. Additionally, we explored the relationships between various patent attributes, such as citation counts and legal statuses, using bubble charts and other visual tools. This EDA provided a comprehensive overview of the dataset, ensuring that our subsequent clustering analysis was well-informed and targeted.

4.1 Data collection

This paper uses a patent databased called the (Lens, 2024b) which is a comprehensive open-access platform that provides access to patent data. This database was used for patent analysis as this is the same databased used for patent study in the WIPO patent analysis handbook (Oldham, 2022). The classification of patents is done with an International Patent Classification (IPC) code which is administered by the World Intellectual Property Organization (WIPO). Two different patent datasets were downloaded in excel format with the first of them being all patents assigned to the International Patent Classification (IPC) code B64G. This is because B64G represents Cosmonautics, Vehicles or Equipment therefor. The reason for using this dataset is because cosmonautics is the science and technology of spaceflight (Gruntman, 2007), i.e. all the patents will be space related. Aside from this, we used a search query[1] of the Lens database. This search string was used since these were frequent words obtained during **(paper 2**) space related systematic review. Both these datasets were downloaded on the 18th of July 2024 with the aim of capturing all space related patents. After downloading both datasets, we then went through a data cleansing process by removing all duplicate patents leaving us with a final dataset of 77,233 patents. From this some exploratory data analysis was done on this dataset and the debris data set in which we describe below. After the preparation of the data the rest of the analysis is done using python programming language.

4.2 Debris dataset creation

To create the space debris dataset, we created a filter to search for debris related space patents. This search consisted of filtering out patents that did not have the term "debris" in either the abstract, title or non-patent literature (NPL) citations of the patent. NPL citations refer to references from non-patent sources like academic papers and technical reports, used to provide context and support for the invention's claims (Verbandt and Vadot, 2018). This filtration reduced the full space patent dataset from 77,233 to 756 patents relating to space debris.

4.3 IPC Code Distance Matrix

The creation of the distance matrix has two separate methods leading to two different types of distance matrices, one when creating the distance matrix for the IPC codes, the second method being the creation of a distance matrix with patent display keys i.e. patent IDs.

The first distance matrix method is for IPC codes and uses two datasets. The first being the normal patent dataset mentioned in section 4.1 and the second being the IPC Index sheet which is a sheet containing all the IPC codes and their relevant descriptions from WIPO. We started by extracting the unique IPC codes from patent dataset, with each column corresponding to different patents. We then cross-referenced these codes with the IPC Index dataset to filter and obtain the codes from the IPC Index sheet that are present in the patent dataset with their description.

After this we then created a metric to measure the similarity of each IPC code to each other which would later be converted into a distance matrix. This involved the combination of two separate IPC calculations, structural and semantic similarity. To calculate the structural similarity between IPC codes we first split the IPC codes into segments: section, class, subclass, group, and subgroup which can be seen in **Table 1**. Each segment was then given a weighting (see **Table 1**). When comparing two IPC codes each level is checked from order of least weight till most and the score is then totalled. When a level does not match the score is then calculated without considering the rest of the code. For example, comparing G01M7/08 to G01S7/08 you would get a similarity score of 0.25.

[1] (Title: (astro* OR (cosmo* OR (spacecraft* OR ("space exploration" OR (rocket* OR orbit*))))) AND (Abstract: (astro* OR (cosmo* OR (spacecraft* OR "space exploration" OR (rocket* OR orbit*))))) OR Claims: (astro* OR (cosmo* OR (spacecraft* OR ("space exploration" OR (rocket* OR orbit*))))))

Table 1: Example breakdown of IPC code (B64G1/66)

Level	Weighting	Symbol	Description
Section	0.10	B	Performing operations; transporting
Class	0.15	64	Aircraft; aviation; cosmonautics
Subclass	0.20	G	Cosmonautics; vehicles or equipment therefor
Group	0.25	1	Cosmonautic vehicles
Subgroup	0.30	66	Arrangements or adaptations of apparatus or instruments, not otherwise provided for

Next, we calculated the semantic similarity which is done by comparing the descriptions for each IPC code. Processing the descriptions consisted of first tokenizing the descriptions, removing stop words and characters (commonly used words e.g. like, the, with, !, £, &). After this is done the semantic similarity is calculated as the ratio of shared words to the total number of unique words between the two descriptions.

To obtain a final similarity score between two IPC codes, we combined the structural similarity and semantic similarity using a weighted approach, with structural similarity contributing 70% to the final score and semantic similarity contributing 30%. This balanced the importance of both the structural classification of IPC codes and the actual content described by those codes. The higher weighting was placed on the IPC code over the description because the codes represent sections that showcase similarity, added to this the descriptions of similar IPC codes may not necessarily share similar words which caused us to place more importance on the section level over the description.

Doing this calculation to every code creates a matrix where every IPC code has a similarity calculation to every other IPC code between 0 and 1, with 0 being no similarity at all and 1 being perfectly similar, representing the same IPC code. To obtain the distance matrix we simply did 1 – similarity matrix.

4.4 Display Key Distance Matrix

The creation of the distance matrix for the Display Keys involved a comprehensive methodology, similar to the distance matrix creation above, that integrates both textual and structural similarity calculation between patents.

To calculate the textual similarity between patents, we focused on the text contained within the abstract, title or NPL citations. The preprocessing of this text was carried out in several stages. We used the TreebankWordTokenizer from the Natural Language Toolkit (NLTK) to break down the text into individual tokens, facilitating further processing. After this common stop words were removed using the NLTK's predefined list. The WordNetLemmatizer was then used to reduce words to their base or root forms, ensuring consistency in how different forms of the same word were treated. Following preprocessing, we calculated the semantic similarity between patents using cosine similarity. This was achieved by applying a pre-trained Word2Vec model, which provided 300-dimensional vector representations of words (Eshetu et al., 2020). The cosine similarity between these vectors was then normalized to produce a score between 0 and 1, with 1 indicating identical semantic content between the patents. In parallel, we calculated the structural similarity between patents based on their IPC codes the same way we did in the previous distance matrix.

The final similarity score between two patents was a weighted combination of their textual and structural similarities. Structural similarity contributed 80% to the final score, while textual similarity accounted for the remaining 20%. This weighting was chosen to emphasize the importance of the structured IPC classifications, while still capturing the semantic content of the patents.

The similarity scores were used to construct a similarity matrix, where each patent was compared to every other patent in the dataset. This matrix was then converted into a distance matrix by subtracting the similarity scores from 1, where a higher distance value indicates lower similarity between patents.

4.5 IPC Code Clustering Algorithm

After constructing the distance matrix, the next step involved applying clustering techniques to group similar IPCR codes based on our precomputed IPC code distance matrix. To achieve this, we utilised the DBSCAN algorithm, and network visualization to uncover patterns and relationships among the IPCR codes. Below, we describe each step in detail

For the clustering analysis three sheets were used, the main debris patent data set, the IPC Index and the IPC code distance matrix. Next all the blanks in the distance matrix were replaced with 0 as these represented codes being tested against themselves, meaning the score should be 0 showcases perfect similarity. We then matched the IPCR codes from the distance matrix with those in the IPCR Index to get detailed descriptions of each IPCR code. Next, we used the Multi-Verse Optimizer[2] (MVO) to optimize the parameters for the DBSCAN clustering algorithm, specifically eps and min_samples (see Appendix 1 for more detail)(Lai et al., 2019). We then used the silhouette score which measures how well-separated the resulting clusters are. We ran the MVO algorithm ten times to find the optimal eps and min_samples values, which were then averaged for stability. We then applied Multidimensional

[2] The Multi-Verse Optimizer (MVO) works by treating each potential solution to an optimization problem as a "universe." It improves solutions by simulating the exchange of information between universes: better solutions act like "white holes," sharing their attributes with others, while poorer solutions behave like "black holes," absorbing new characteristics. Additionally, random adjustments called "wormholes" allow universes to explore new areas of the solution space, helping the algorithm to balance the search between refining current solutions and discovering new ones (Mirjalili et al., 2016).

Scaling (MDS)[3] to reduce the dimensionality of the distance matrix, allowing us to visualize the clusters in a 2D space (Buja et al., 2008).

We then constructed a network graph, where each node represents an IPC code, and edges represent IPC codes with shared patent application numbers. Nodes were then filtered by country and the degree of connectivity (i.e., the number of connections each node has). Next, we visualized the final network, where each cluster was assigned a distinct colour, and noise (un-clustered nodes) was omitted from the visualization. Finally, we extracted and displayed keywords for each cluster by analysing the descriptions of the IPCR codes within each cluster, providing a summary of the key themes or technologies represented in each cluster.

4.6 Display Key Clustering Algorithm

In this section, we outline the steps taken to preprocess the patent debris data, reduce its dimensionality and apply clustering techniques to reveal patterns and relationships.

When shifting the focus to display keys and not IPC codes representing nodes the data points resulted in a dimensionality of 756, which is considerably high. Dimensionality refers to how many variables, features or attributes each point in a dataset has (Del Giudice, 2021). For example, if a dataset only measured hight it is 1-D, when you add weight, its 2-D when you add age it becomes 3-D and so on. For us this meant that each point in our display key distance matrix had 756 features. Chen et al (2021) argue that high dimensional data affects the DBSCAN algorithm by yielding considerable redundant distance computations which can affect the algorithms' ability to form clusters. This hurdle was overcome by using principal component analysis[4] (PCA) to simplify high dimensional data while still retain trends and patterns present in the data (Lever et al., 2017). Initially, PCA was run without specifying the number of components, allowing us to analyse the explained variance across all components. The variance was plotted to determine the number of principal components that retain 90% of the total variance of the data, which is essential for balancing data simplification with information preservation. After identifying the optimal number of components (7), PCA was re-applied to the data, retaining only those components that captured 90% of the variance. With the reduced data from PCA, we computed the pairwise Euclidean[5] distances to form a new distance matrix. This matrix served as the input for the DBSCAN clustering algorithm. Similar to the IPC code clustering method, MVO was used to simplify the eps and min_samples parameters by maximising silhouette score. Moreover, we followed the same method above using MDS to project the distance matrix unto a 2-dimensional space. Next a network graph was constructed where each node represented a patent (display key) and edges

[3] Multidimensional Scaling MDS is a technique used for dimensionality reduction, which aims to visualise the structure of high-dimensional data in a lower-dimensional space, typically two or three dimensions. The main goal of MDS is to preserve the pairwise distances between points in the high-dimensional space as much as possible in the reduced-dimensional representation (Buja et al., 2008).

[4] PCA works by identifying the directions (principal components) in which the data varies the most, and then projects the data along these directions, effectively reducing the number of dimensions while preserving as much variability as possible.

[5] Pairwise Euclidean distances involve calculating the straight-line distance between each pair of points in a given set. This distance is determined by applying the Pythagorean theorem to the differences in their coordinates. When you compute these distances for every possible pair of points in a set, the result is a matrix where each element represents the distance between two points (Achlioptas, 2003).

were formed between nodes that shared IPC codes. Then, the nodes were color-coded based on their cluster assignment and filtered by country for the DBSCAN algorithm to generate the visualisation. Finally, we extracted and presented keywords for each cluster by analysing the shared title, abstract and NPL citations of each patent in the visualisation, offering a summary of the main themes or technologies represented in each cluster.

5 Results

Before applying the DBSCAN algorithm, exploratory data analysis was conducted to uncover any key patterns in the data. This section provides insight into the distribution of patent, frequency, trend, distribution and citation analysis providing a foundation for understanding the clustering results. It should be noted that each form of analysis was performed on the two datasets, space patents and space debris patents.

5.1 Exploratory Data Analysis

5.1.1 Applicant Analysis

Figure 1: Top 20 Patent Applicants

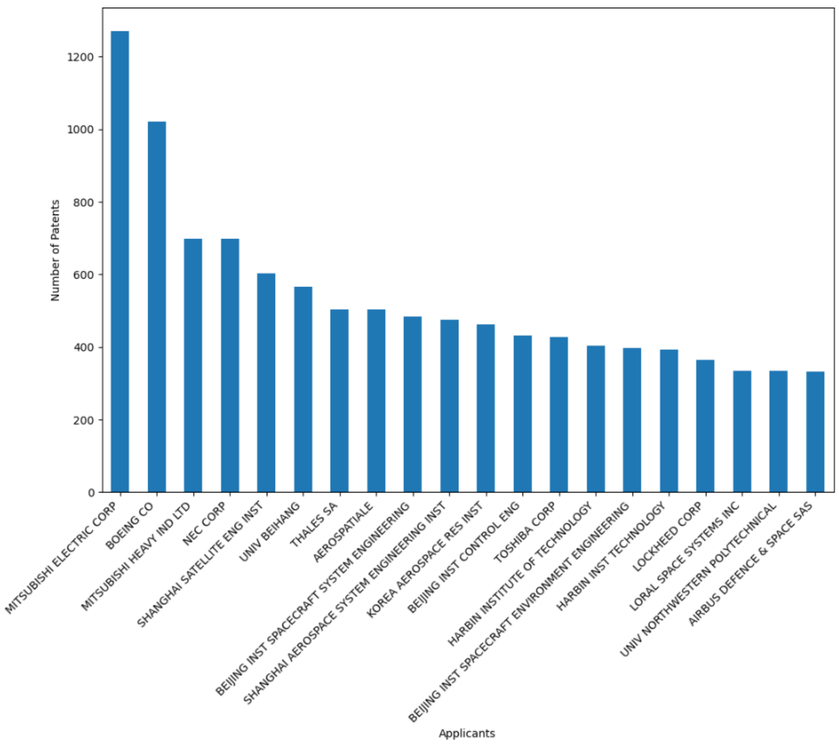


Figure 2: Top 20 Debris Patent Applicants

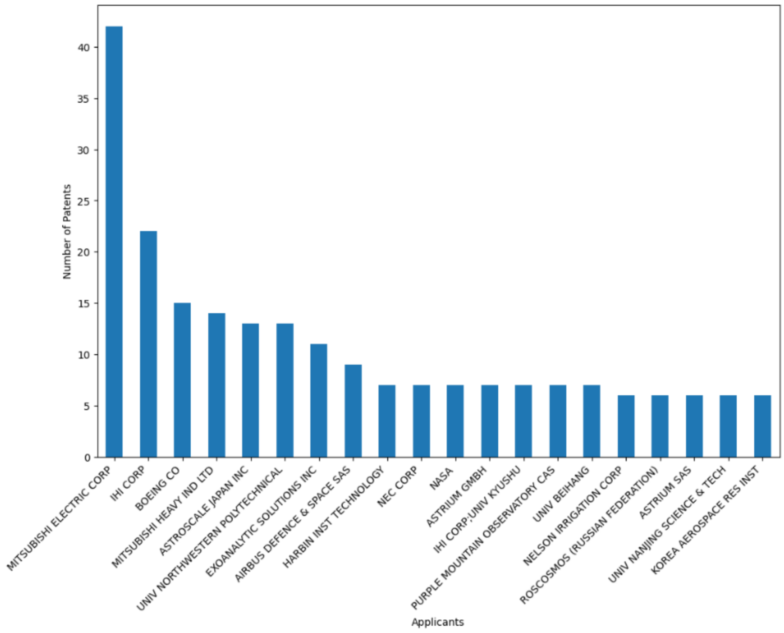


Figure 1 and Figure 2 showcase the top 20 patent applicants overall and in debris-related technologies. In both figures, Mitsubishi Electric Corp has the highest number of total applications holding over 1200 patents in total and more than 40 debris-related patents. However, the distribution of patent ownership is more concentrated in the debris-related field, with a steeper drop-off after the top few applicants. For instance, while Boeing Co and Mitsubishi Heavy Ind Ltd are major contributors in both categories, the overall patent chart shows a more gradual decline in the number of patents across the top 20 applicants, whereas the debris-related chart displays a more significant gap between the leading companies and the rest. This suggests that debris-related patenting is a more specialized area with fewer dominant players compared to overall patent activity, where patenting is more evenly distributed among the top applicants.

5.1.2 *Patent Frequency Analysis*

Figure 3: Top 20 IPC Codes with Descriptions

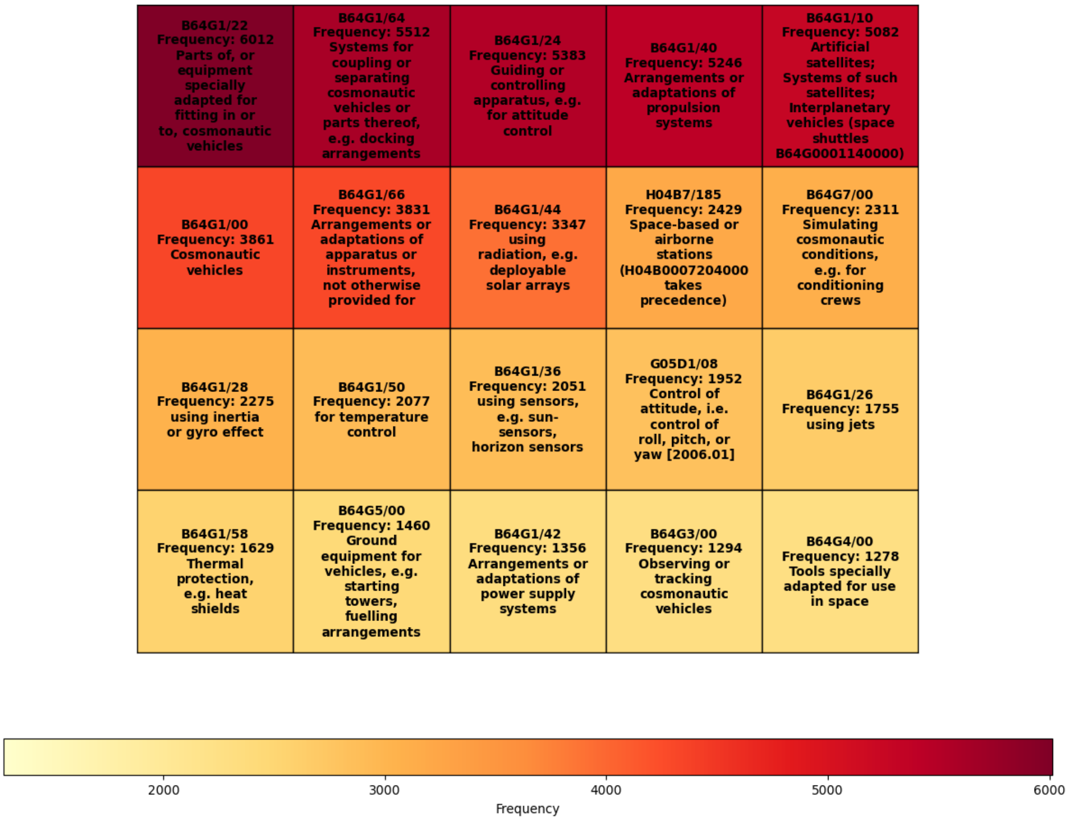


Figure 4: Top 20 Debris IPC Codes with Descriptions

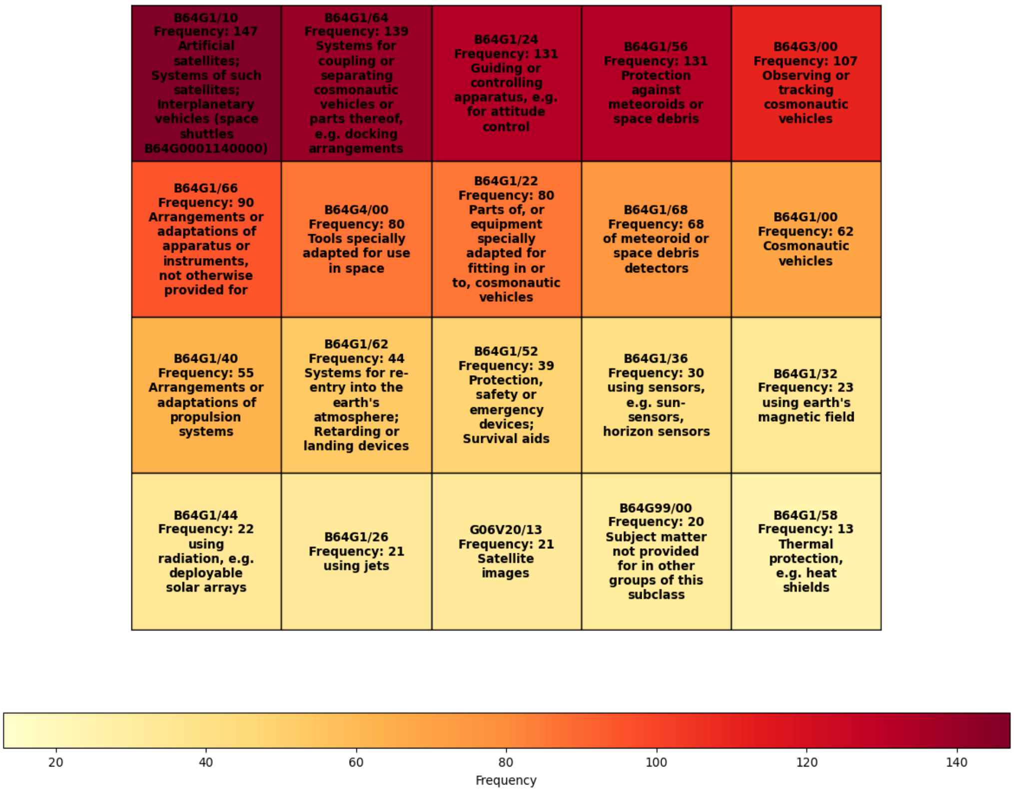


Figure 3, showing the patent dataset, shows that the most frequent IPC codes are B64G1/22 (parts of or equipment adapted for cosmonautic vehicles), B64G1/64 (systems for coupling or separating cosmonautic vehicles, such as docking arrangements), and B64G1/24 (guiding or controlling apparatus like attitude control). These technologies are fundamental to space missions, emphasizing spacecraft assembly, vehicle construction, and control systems. In Figure 4, the debris-related dataset, the top IPC codes are B64G1/10 (artificial satellites and interplanetary vehicles), B64G1/64 (coupling and docking systems), and B64G1/24 (guiding or controlling apparatus like attitude control), which ties with B64G1/56 (protection against meteoroids or space debris). The equal frequency of B64G1/24 and B64G1/56 highlights that both guiding and control technologies as well as debris protection are pivotal to debris management efforts. The presence of B64G1/56 indicates significant innovation focused on protecting spacecraft from debris impacts, while B64G1/10 underscores the importance of satellite systems in monitoring and mitigating space debris. The overlap in B64G1/64 across both datasets suggests that docking and coupling systems are critical not only for general space operations but also for space debris management, where these technologies play a crucial role in debris removal and maintenance. This analysis demonstrates that while there is shared technological development between general space activities and debris management, debris-related patents tend to emphasize protective, and mitigation technologies designed to address the increasing challenge of space debris.

5.1.3 Patent Trend Analysis

Figure 5: Number of Patents per Year

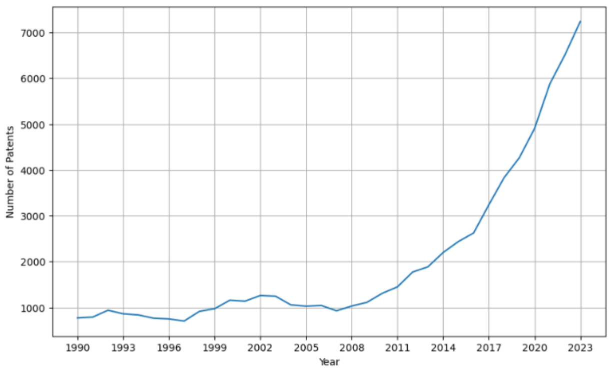


Figure 6: Number of Debris Patents per Year

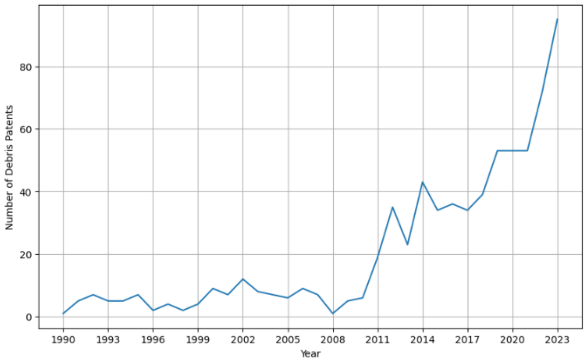


Figure 5 and Figure 6, present trends in patent activity, with the first depicting the number of patents per year and the second showing the total number of debris patents per year. While both graphs display a general increase in patent activity over time, the trend in debris-related patents increases significantly from 2010 onwards, with a rapid spike starting around 2017 and continuing through 2023. On the other hand, the total patent count follows a more gradual, sustained growth pattern starting in the early 2000s, with a notable acceleration after 2015. This suggests that while overall innovation has increased, debris-related technologies have experienced a more sudden and intense growth in recent years, likely driven by emerging challenges or technological breakthroughs in this specialised field. The growth in debris patents as a proportion of total patents appears to be accelerating, indicating a growing focus on addressing debris-related issues.

Figure 8: Number of Patents Filed Over Time for Top 10 Countries

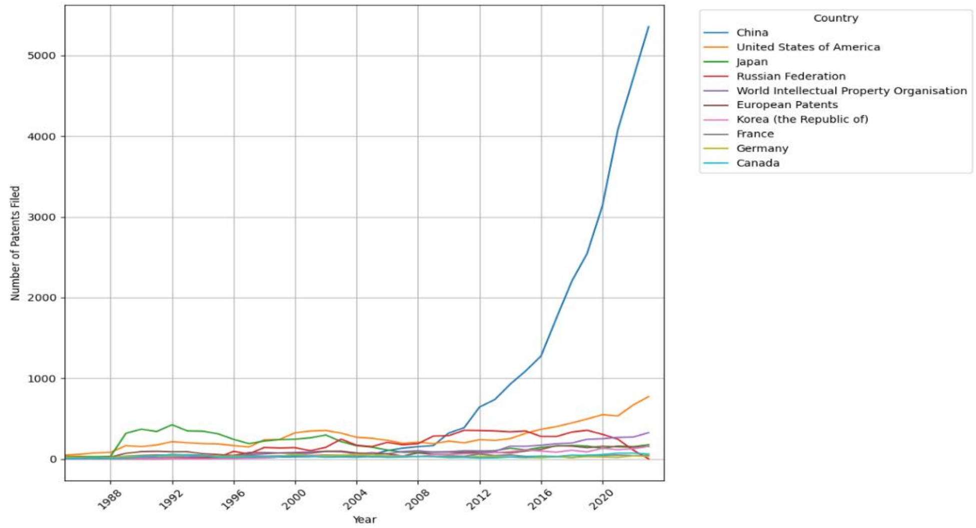


Figure 7: Number of Debris Patents Filed Over Time for Top 10 Countries

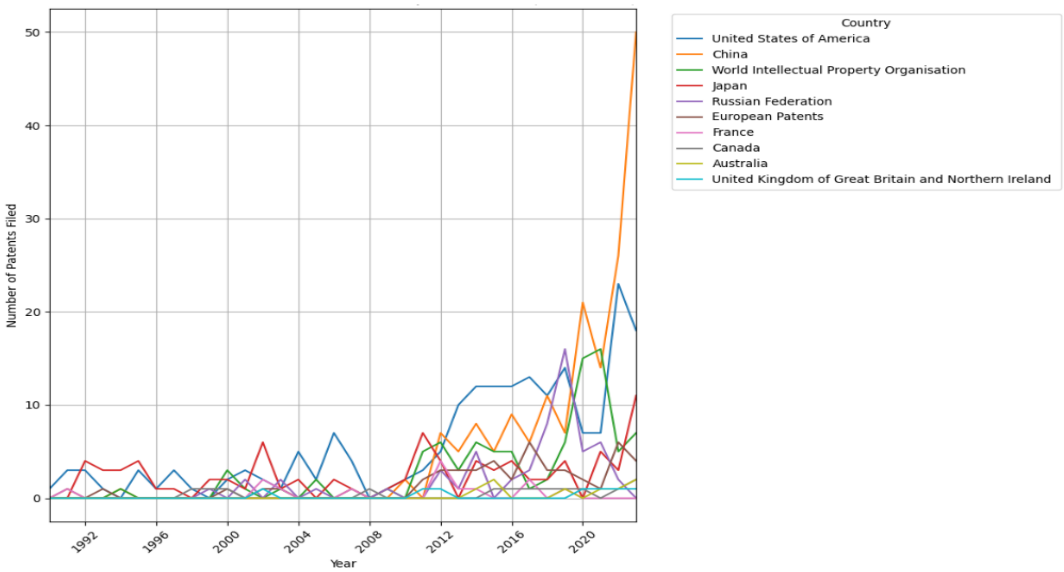


Figure 8 and Figure 7, compare the number of patents filed over time by 10 countries. Figure 8 shows a dramatic rise in overall patent filings by China starting around 2010, far surpassing other countries by 2023. The United States follows with a steadier, moderate increase, while other countries remain relatively flat in comparison. In contrast, Figure 7 shows the United States and China leading, with a sharp rise in debris patents from both countries post-2012. While China leads in overall patent activity, the debris-related patent filings are more distributed across multiple countries, with significant contributions from the U.S. and Japan. Notably, the debris-specific graph demonstrates a recent surge in activity, particularly in the last decade, suggesting growing global interest in debris management technologies, albeit on a smaller scale compared to overall patent filings.

5.1.4 Patent Distribution analysis

Figure 9: Distribution of Patents by Country (1990-2023)

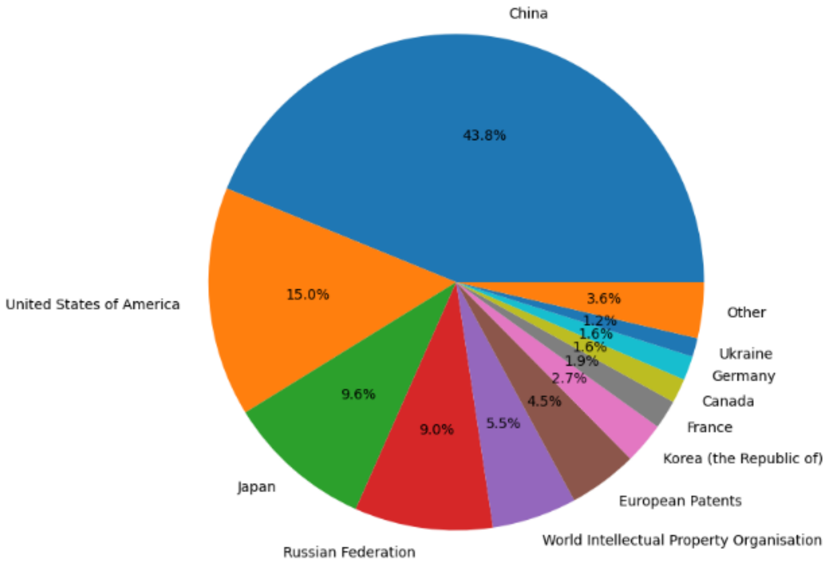


Figure 10: Distribution of Debris Patents by Country (1990-2023)

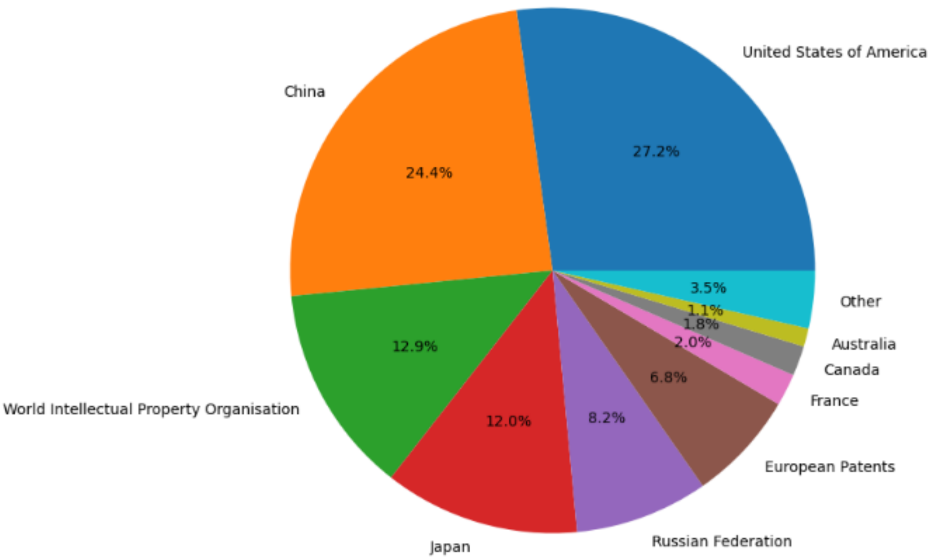


Figure 9 and Figure 10 compare the distribution of patents and debris-related patents filed by countries from 1990 to 2023. In Figure 9, China dominates with 43.8% of the total patents, followed by the United States (15%) and Japan (9.6%), while the remaining countries account for significantly smaller shares. In contrast, Figure 10**,** which focuses on debris-related patents, shows a more balanced distribution, with the United States leading at 27.2%, followed by China at 24.4%, and a more substantial contribution from Japan (12.9%) and the World Intellectual Property Organisation (12%). This shift highlights that, while China leads in total patent filings, the United States plays a more prominent role in debris-related innovation, with more countries actively contributing to this specialized area than in overall patent activity. The data suggest that debris-related innovation is more evenly distributed among the top patent-filing countries, reflecting its growing global importance.

Figure 11: Distribution of Patent Document Types

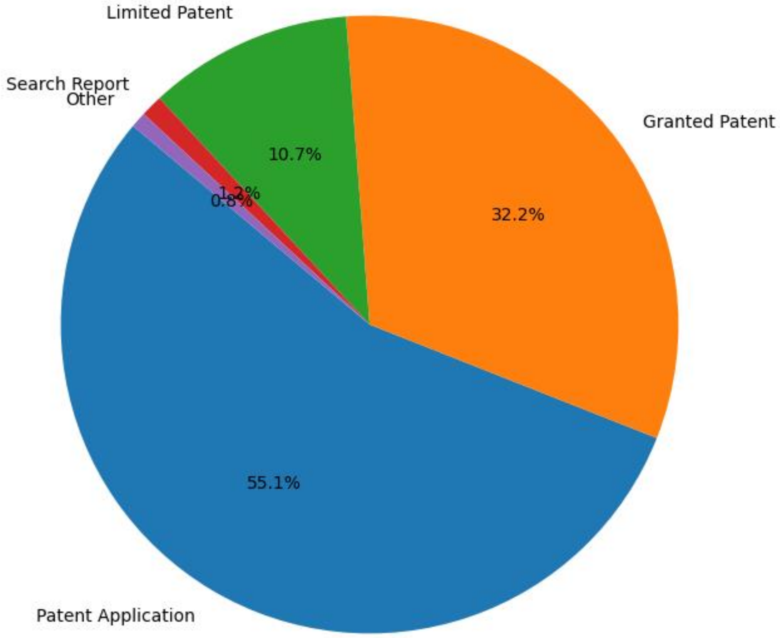


Figure 12: Distribution of Debris Patent Document Types

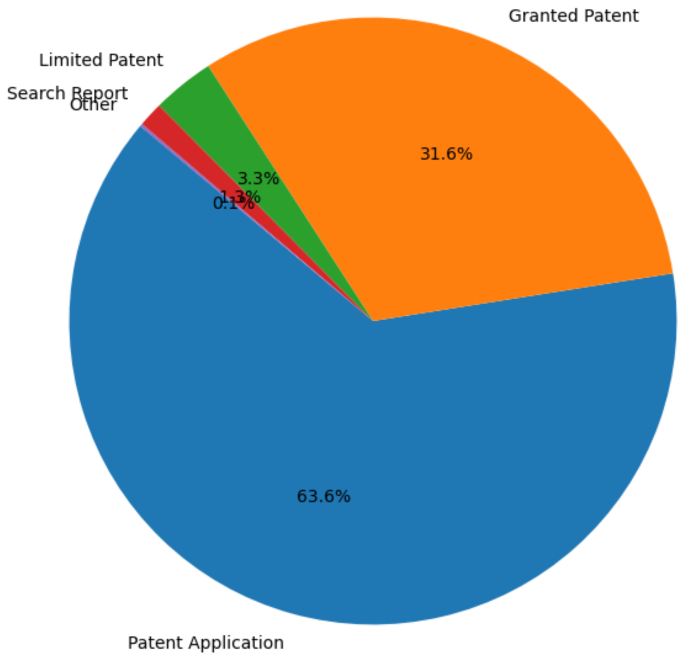


Figure 11 and Figure 12 illustrate the distribution of document types[6] for overall patents and debris-related patents from 1990 to 2023. In both figures, patent applications represent the largest share, accounting for 55.1% of all patent documents and 63.6% of debris-related documents. Granted Patents

[6] **Granted Patent**: A patent that has been approved, giving the holder exclusive rights to the invention. **Patent Application**: A filed request for a patent that is under review but not yet granted. **Limited Patent**: A patent with restricted rights or a shorter duration compared to a full patent. **Search Report**: An analysis of existing patents and literature to determine the novelty of a patent application. **Other**: Miscellaneous documents related to patents, such as legal or administrative records (Lens, 2023).

follow, making up 32.2% of total patent documents and 31.6% of debris-related documents, indicating a similar proportion of granted patents in both categories. However, debris-related patents show a slightly higher proportion of patent applications compared to overall patent activity, suggesting a larger number of pending or new innovations in the debris management field. Smaller categories like Limited Patents, Search Reports, and Other remain relatively minor in both contexts, with debris-related patents showing slightly fewer of these document types, further emphasizing the growing activity in patent applications for debris technologies. This indicates an emerging and still-developing field, with a significant portion of patents still in the application phase.

5.1.5 Citation Analysis

Figure 13: Top 100 Patents by Cited by Patent Count

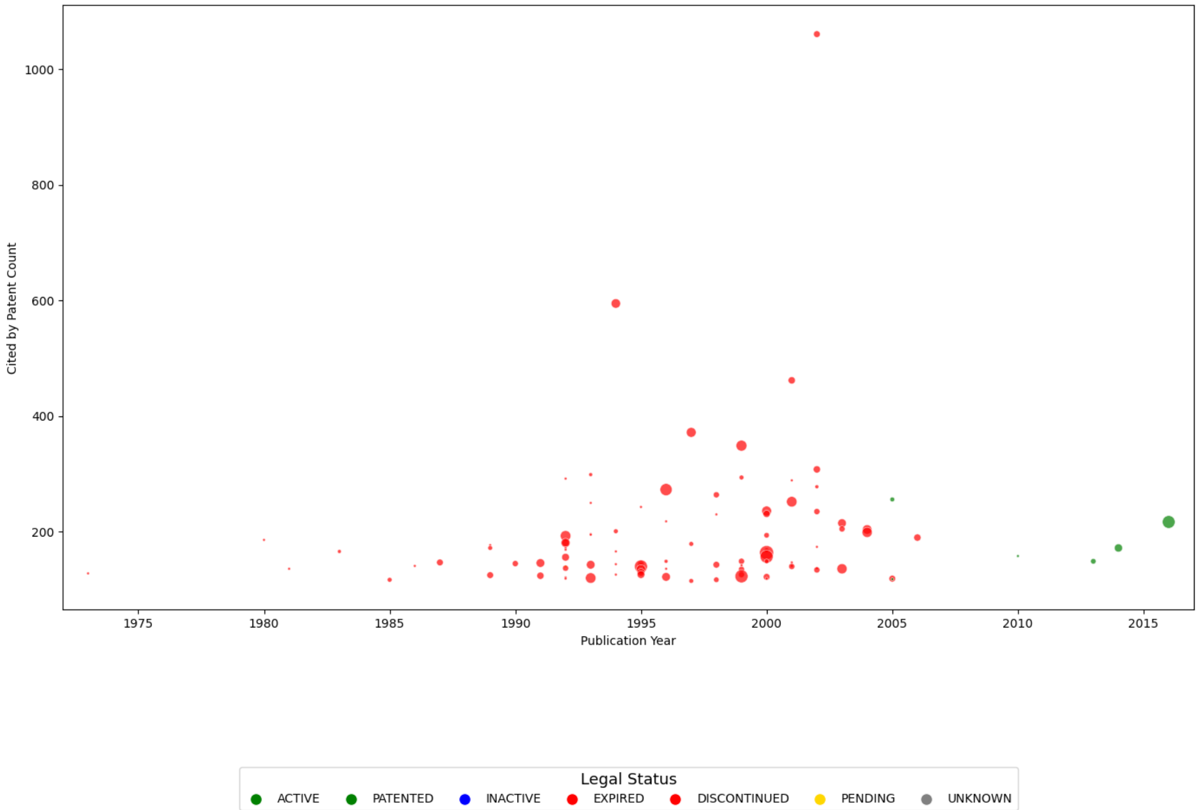


Figure 14: Top 100 Debris Patents by Cited by Patent Count

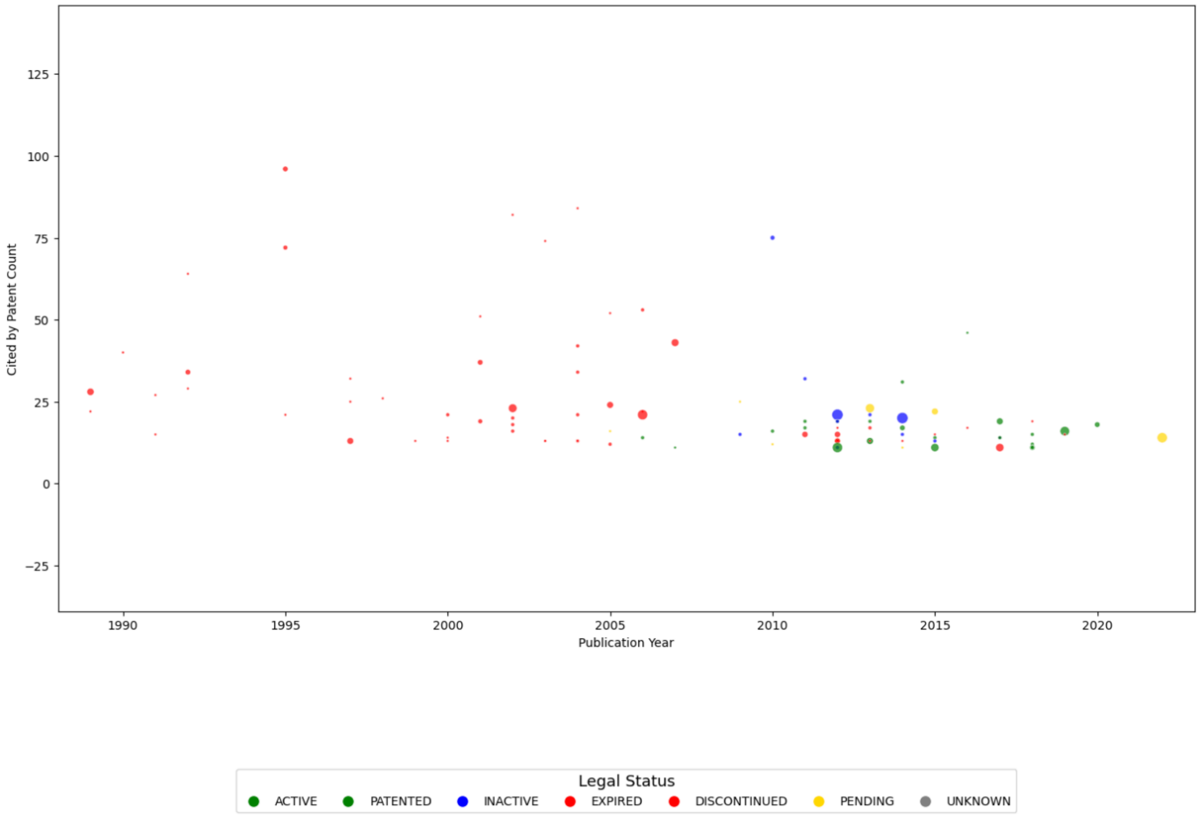


Figure 13 and Figure 14 showcase the top 100 patents and the top 100 debris-related patents by the number of citations received, which is how many subsequent patents have referenced this patent (Lens, 2024a). Figure 13 shows that the most highly cited patents date from the mid-1990s to the early 2000s, with one cited over 1,000 times, and a concentration of expired patents (red dots) dominating this category. In contrast, Figure 14, focusing on debris-related patents, shows far fewer citations overall, with the highest count barely reaching 100 citations. There is also a more balanced distribution of active, patented, and pending debris-related patents compared to the larger proportion of expired patents in the general dataset. This indicates that while debris-related patents are still an emerging field with less historical activity and lower citation counts, recent patents in this area have garnered increasing attention, with many still active or pending.

Figure 16: Top 100 Patents by Cites Patent Count

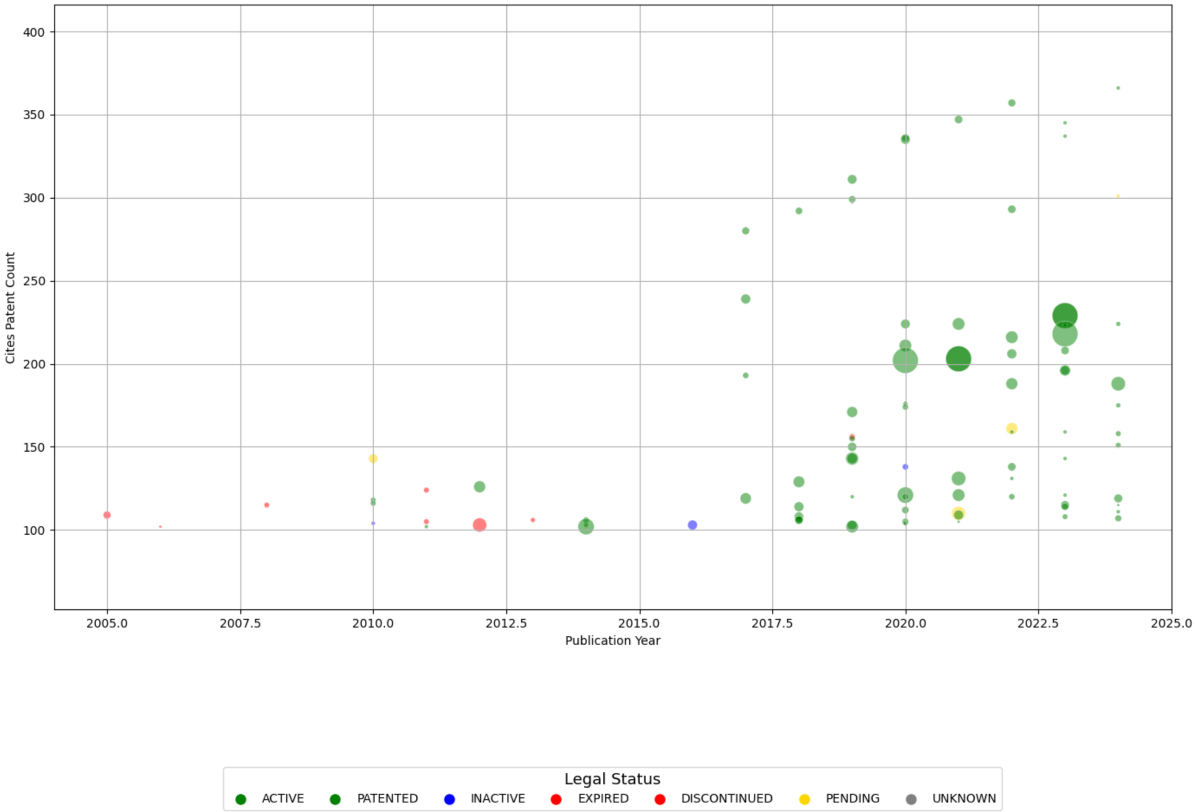


Figure 15: Top 100 Debris Patents by Cites Patent Count

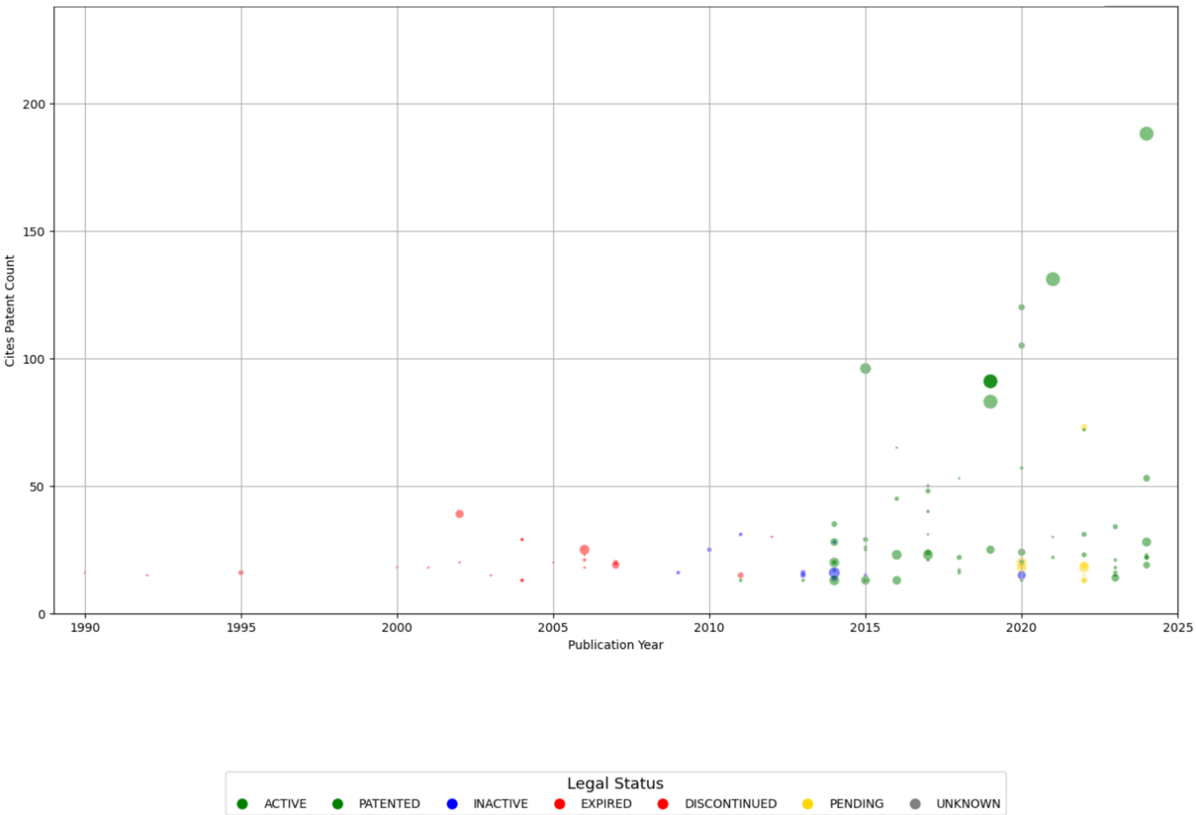


Figure 16 and Figure 15 showcase the top 100 patents and the top 100 debris-related patents by the number of citations received (how many patents this patent has referenced) over time (Lens, 2024a). Figure 16 shows a significant concentration of highly citing patents from around 2017 onward, with some having over 300 citations, and a large proportion of these patents are still active or patented (green). In contrast, Figure 15, focusing on debris-related patents, has fewer total citations, with the highest cited patents reaching just under 200. Most debris patents have cited much less frequently, and there is a broader mix of patent statuses, including a small but noticeable proportion of expired (red) and pending (yellow) patents. Overall, the data suggests that general patents tend to cite other patents more than debris-related patents do. This indicates that while debris patents are a growing field, they tend to cite fewer existing patents compared to the general pool of patents.

5.2 IPC Code DBSCAN

This section provides insight into the IPC code clustering results, unveiling underlying patterns and groups in the patent data. It should be noted that each form of clustering analysis was performed on the two datasets, space patents and space debris patents. Added to this, Italy had no identified clusters, as the data revealed that while Italy help space related patents none were focused on space debris according to our filtering method.

5.2.1 All countries

Figure 17: Visualisation of All Countries IPC Debris Patents Clusters

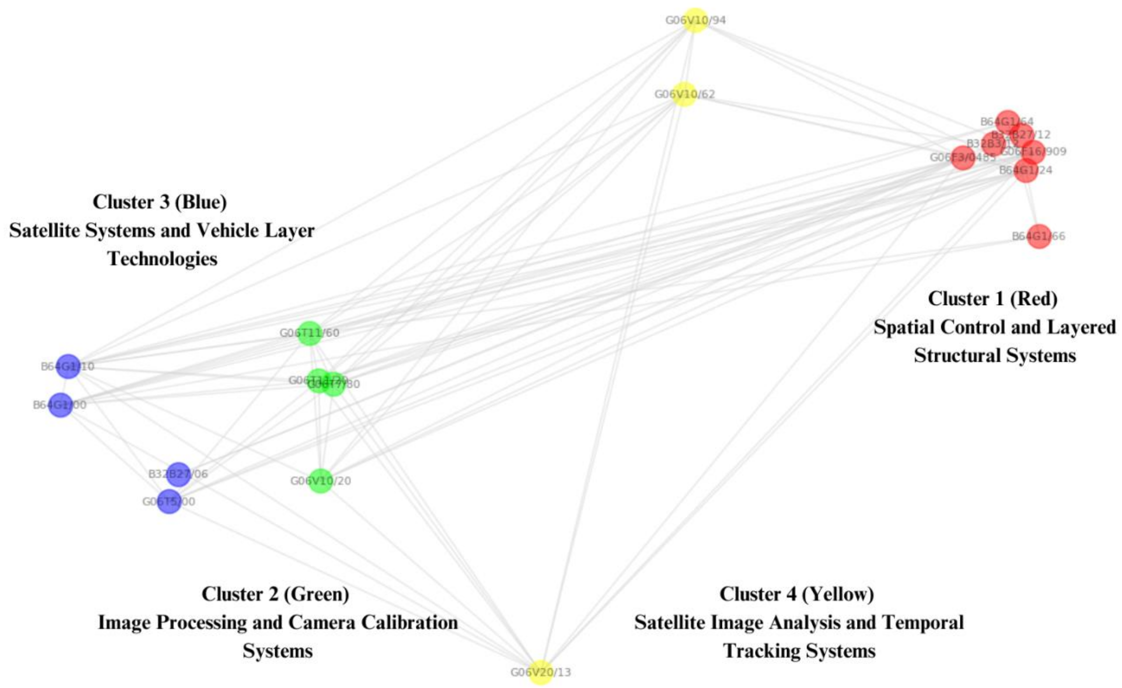


Figure 17 represents the results of the DBSCAN clustering algorithm, highlighting the technological focus of different countries in the field of space debris-related patents. Each colour corresponds to a specific cluster, representing distinct areas of technological innovation.

Cluster 1 (Red): Spatial Control and Layered Structural Systems: are essential for maintaining the reliability of spacecraft, particularly in debris-rich environments. This cluster's tight grouping hints at a concentrated effort by countries or entities working on advanced guidance and control systems, indicating collaboration or parallel development in this field.

Cluster 2 (Green): Image Processing and Camera Calibration Systems: are important for monitoring space debris. The somewhat more separated nature of this cluster reflects a diverse range of technologies and potential applications related to image analysis.

Cluster 3 (Blue): Satellite Systems and Vehicle Layer Technologies: centres on a range of satellite systems and vehicle layer technologies. The proximity of nodes within this cluster highlights the importance of durable satellite construction, with entities likely focusing on reinforcing materials to withstand space debris.

Cluster 4 (Yellow): Satellite Image Analysis and Temporal Tracking Systems: emphasizes satellite image processing. separation of this cluster suggests a high degree of variation of these technologies, particularly in space debris monitoring and analysis.

Overall, the visualization provides insights into how different clusters of technologies are being developed in tandem, showing collaboration and focus across various countries on space debris mitigation and related innovations in the world.

5.2.2 EU

Figure 18: Visualisation of European Union IPC Debris Patents Clusters

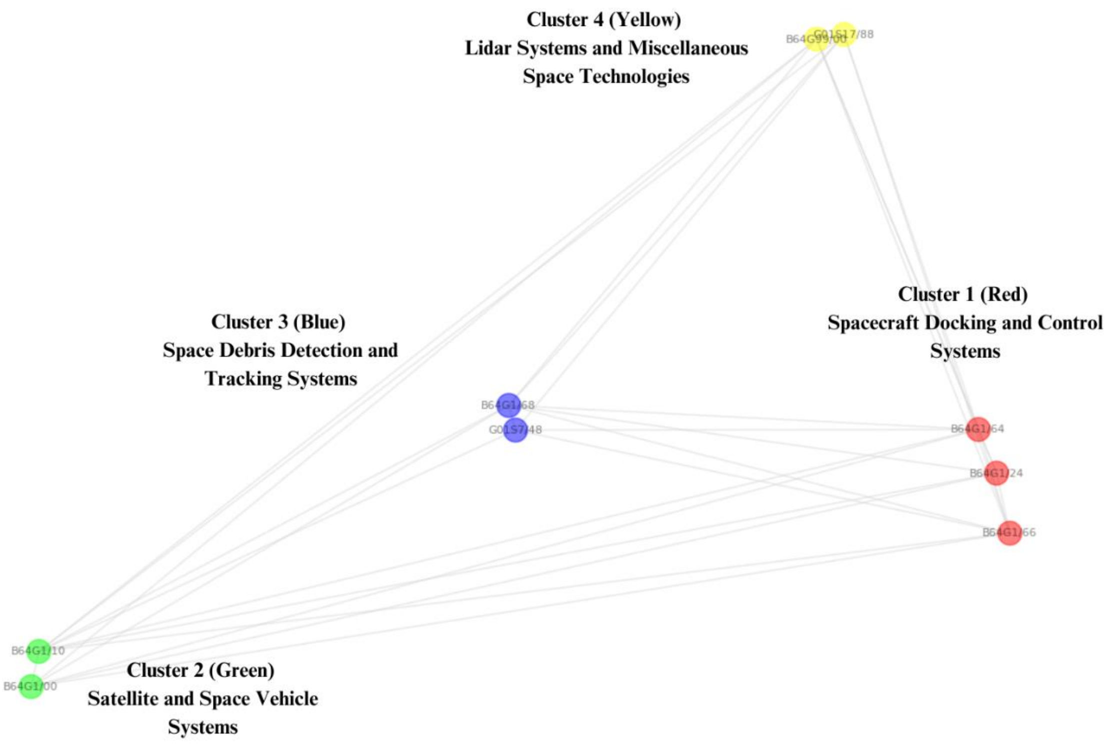


Figure 18 represents the results of the DBSCAN clustering algorithm visualization specific to the EU.

Cluster 1 (Red): Spacecraft Docking and Control Systems: focuses on guiding and controlling spacecraft, essential for safe docking and vehicle manoeuvrability, which are critical in debris-filled space environments.

Cluster 2 (Green): Satellite and Space Vehicle Systems: showcases technologies related to the construction and management of satellites and space vehicles, crucial for space exploration and operations while maintaining resilience against space debris.

Cluster 3 (Blue): Space Debris Detection and Tracking Systems: emphasizes advanced systems for detecting and tracking debris, which are vital for monitoring debris and avoiding potential collisions that could endanger space missions.

Cluster 4 (Yellow): Lidar Systems and Miscellaneous Space Technologies: focuses on Lidar and other unclassified cosmonautic technologies, which contribute to precise measurements, space debris monitoring, and navigation.

This visualization provides insight into the EU's focused technological efforts to address space debris challenges through advanced control systems, satellite management, debris detection, and Lidar applications. These innovations are critical for ensuring the safety and sustainability of space missions in increasingly crowded orbits.

5.2.3 USA

Figure 19: Visualisation of USA IPC Debris Patents Clusters

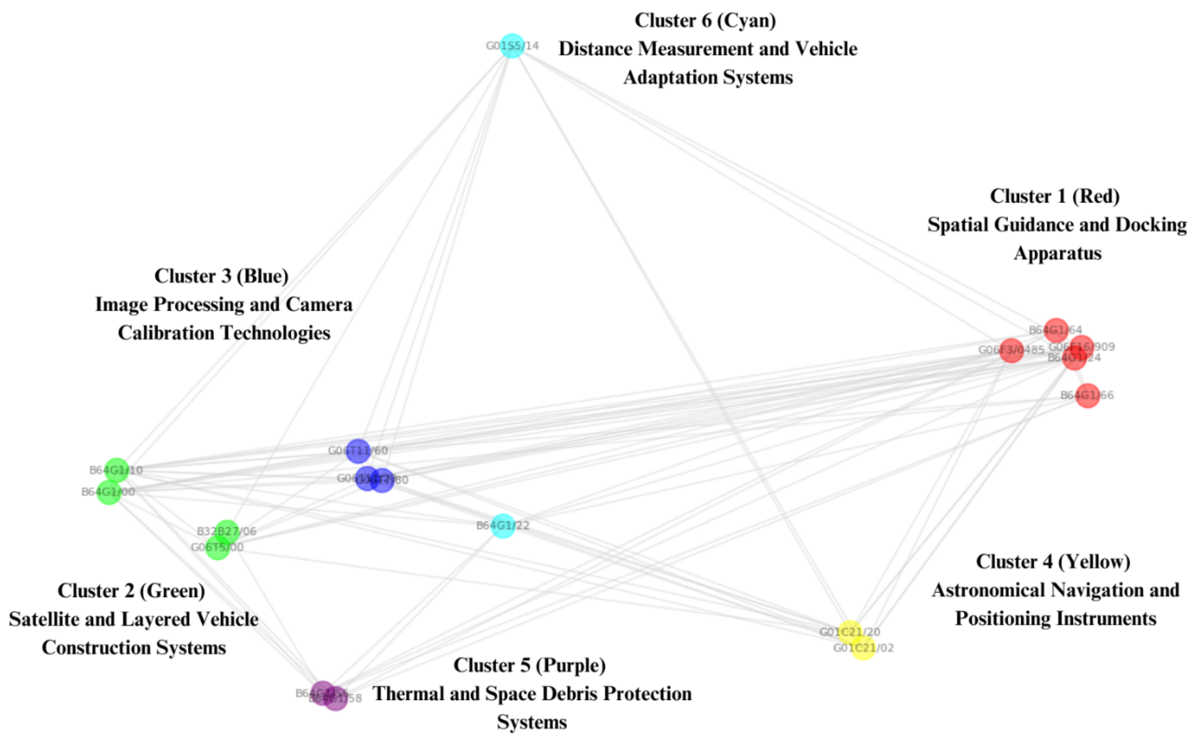


Figure 19 represents the results of the DBSCAN clustering algorithm visualization specific to the United States.

Cluster 1 (Red): Spatial Guidance and Docking Apparatus: shows a concentrated effort on technologies that support spacecraft navigation and docking mechanisms, which are essential when operating in debris-heavy environments.

Cluster 2 (Green): Satellite and Layered Vehicle Construction Systems: centres around resilient satellite and spacecraft designs, utilizing layered materials to enhance structural durability

Cluster 3 (Blue): Image Processing and Camera Calibration Technologies: highlights a concentration of patents focused on improving satellite imagery and debris detection through advanced camera systems and image processing.

Cluster 4 (Yellow): Astronomical Navigation and Positioning Instruments: a key technology for navigating spacecraft by using astronomical reference points to avoid debris.

Cluster 5 (Purple): Thermal and Space Debris Protection Systems: suggests that the U.S. is focused on technologies that protect spacecraft from extreme heat and space debris impact.

Cluster 6 (Cyan): Distance Measurement and Vehicle Adaptation Systems: covers technologies that ensure accurate distance measurements and adaptations of spacecraft systems to avoid debris while maintaining optimal performance in space.

Figure 19 shows that U.S. patent innovation is geared towards mitigating the risks posed by space debris. Each cluster reflects a critical component of debris-related technology, from navigation and docking to protection and debris monitoring, underscoring the multifaceted approach required to address space debris challenges.

5.2.4 China

Figure 20: Visualisation of China IPC Debris Patents Clusters

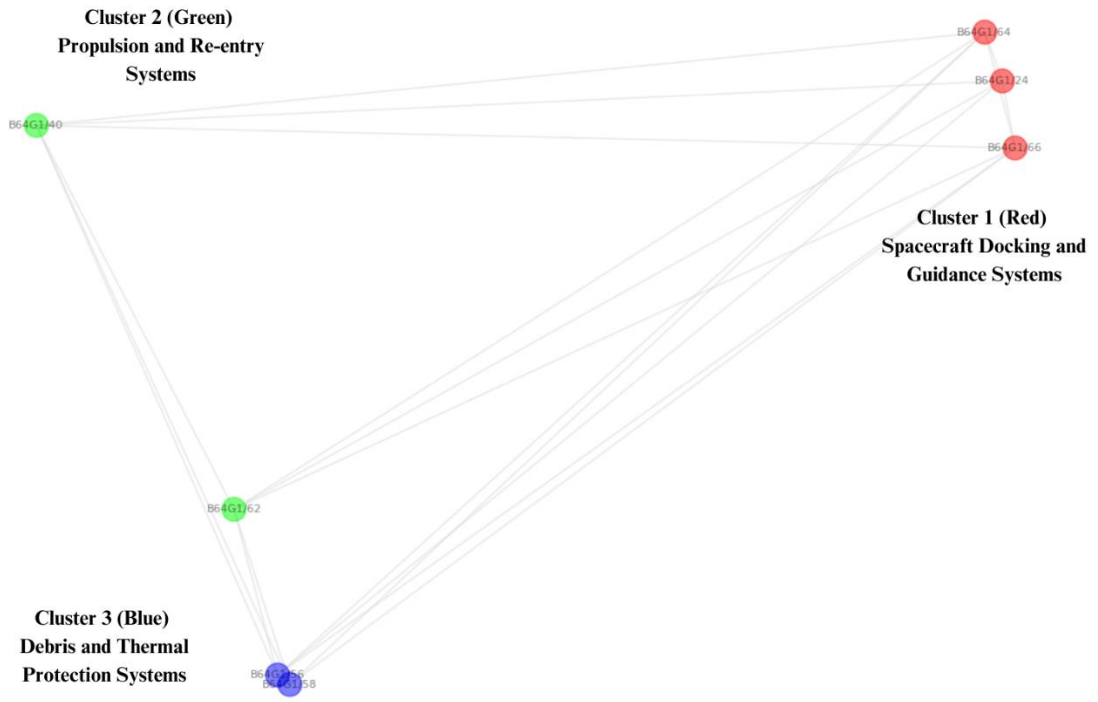


Figure 20 represents the results of the DBSCAN clustering algorithm visualization specific to China.

Cluster 1 (Red): Spacecraft Docking and Guidance Systems: emphasizes patents focused on guiding and controlling spacecraft, particularly during docking operations, ensuring spacecraft can navigate safely and dock without colliding with debris.

Cluster 2 (Green): Propulsion and Re-entry Systems: highlights technologies related to spacecraft propulsion and safe re-entry. These innovations are essential for controlling movement in space and ensuring that spacecraft can return to Earth safely while avoiding collisions with space debris.

Cluster 3 (Blue): Debris and Thermal Protection Systems: focuses on protective technologies, including shields against space debris and thermal protection systems, which are vital for maintaining spacecraft integrity in harsh environments, protecting them from debris impacts, and ensuring they can withstand the extreme temperatures encountered in space.

This visualization suggests that China is concentrating on developing robust systems to address key aspects of space debris risk, from efficient navigation and propulsion to protective measures that ensure spacecraft can operate safely in debris-filled orbits.

5.2.5 *Japan*

Figure 21: Visualisation of Japan IPC Debris Patents Clusters

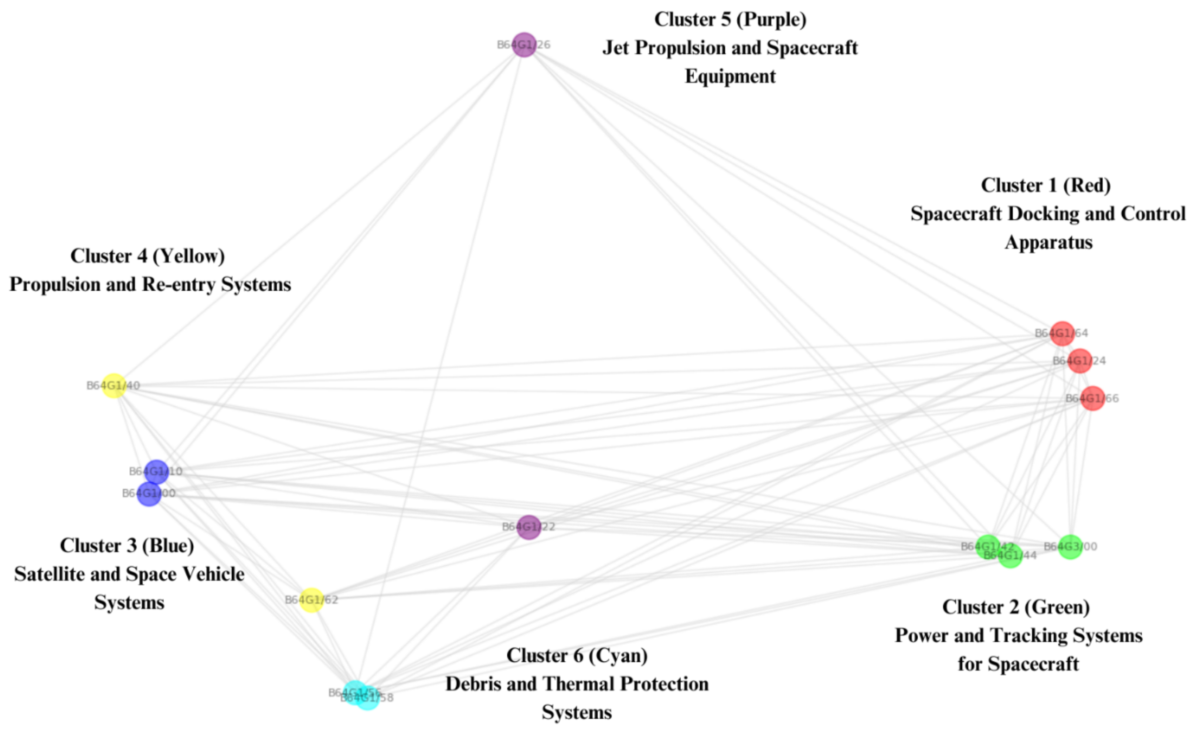


Figure 21 represents the results of the DBSCAN clustering algorithm visualization specific to Japan.

Cluster 1 (Red): Spacecraft Docking and Control Apparatus: highlights innovations related to spacecraft docking and control systems, ensuring safe operations in space environments full of debris. *Cluster 2 (Green): Power and Tracking Systems for Spacecraft:* focuses on power supply systems and tracking technologies, including deployable solar arrays that are essential for ensuring spacecraft can be effectively powered and tracked throughout their missions.

Cluster 3 (Blue): Satellite and Space Vehicle Systems: demonstrates Japan's focus on building resilient satellites and space vehicles designed to manage space debris.

Cluster 4 (Yellow): Propulsion and Re-entry Systems: highlights technologies aimed at ensuring safe spacecraft propulsion and re-entry, which are vital to avoid debris during critical phases of space missions.

Cluster 5 (Purple): Jet Propulsion and Spacecraft Equipment: focuses on advanced propulsion technologies, which are integral to manoeuvring spacecraft efficiently in space while avoiding collisions with debris.

Cluster 6 (Cyan): Debris and Thermal Protection Systems: addresses protective systems against both debris impacts and extreme thermal conditions, ensuring that spacecraft remain intact during their missions.

This visualization provides insight into Japan’s multi-faceted approach to addressing space debris, from improving spacecraft propulsion and control to developing advanced protection systems, ensuring their space missions can navigate and operate safely amidst growing debris challenges.

5.2.6 Russia Federation

Figure 22: Visualisation of Russia IPC Debris Patents Clusters

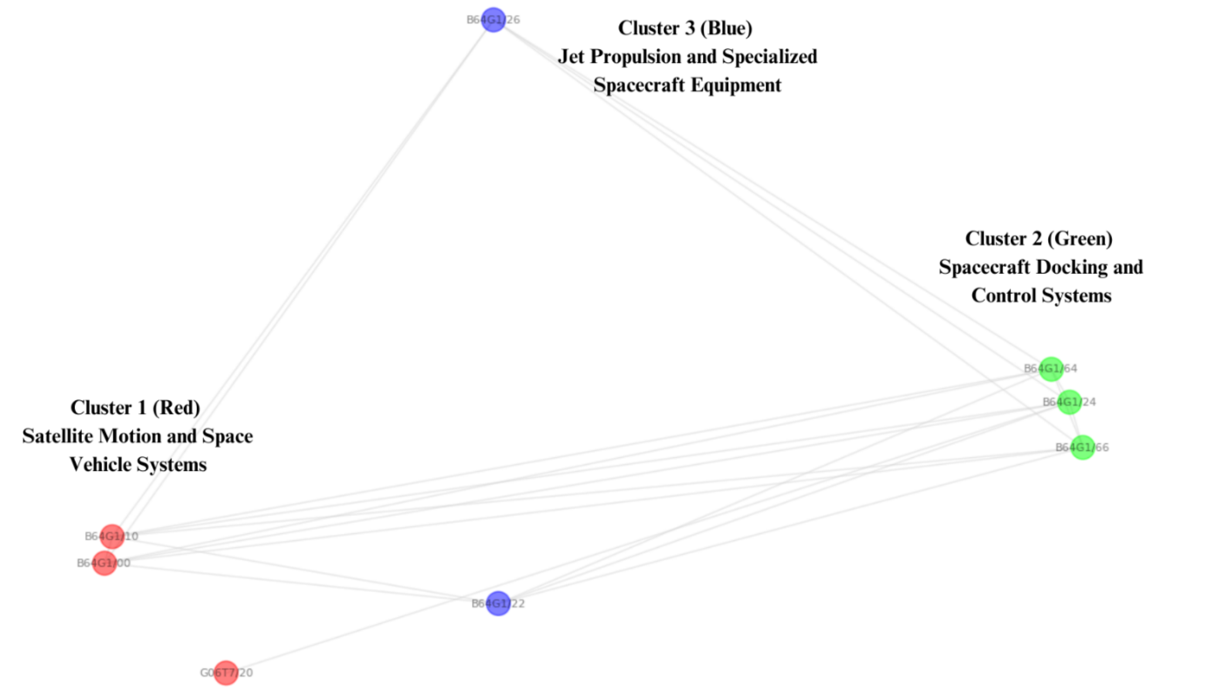


Figure 22 represents the results of the DBSCAN clustering algorithm visualization specific to the Russian Federation.

Cluster 1 (Red): Satellite Motion and Space Vehicle Systems: emphasizes technologies focused on cosmonautic vehicles, artificial satellites, and motion analysis. These systems are crucial for understanding satellite navigation and motion in space.

Cluster 2 (Green): Spacecraft Docking and Control Systems: highlights technologies for guiding, controlling, and docking spacecraft, which are essential for managing spacecraft operations in space. These systems ensure safe docking and attitude control, particularly in environments filled with space debris, where precision is necessary.

Cluster 3 (Blue): Jet Propulsion and Specialized Spacecraft Equipment: focuses on jet propulsion technologies and specialised spacecraft components, which play a vital role in efficient propulsion and the adaptation of spacecraft for exploration while mitigating debris risks.

This visualization reflects Russia’s technological focus on improving spacecraft navigation, control, and propulsion systems to address the growing issue of space debris. The clusters emphasize the importance of manoeuvrability, docking, and propulsion in ensuring the safety and efficiency of spacecraft in debris-laden orbits.

5.2.7 France

Figure 23: Visualisation of France IPC Debris Patents Clusters

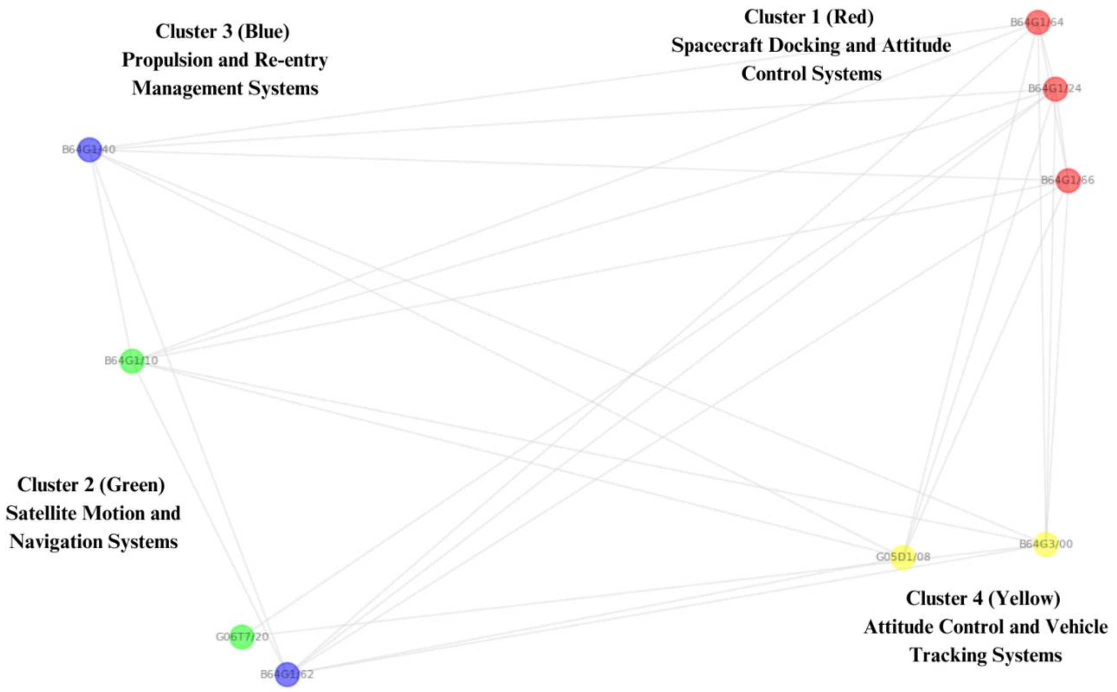


Figure 23 represents the results of the DBSCAN clustering algorithm visualization specific to France.

Cluster 1 (Red): Spacecraft Docking and Attitude Control Systems: emphasizes technologies crucial for guiding spacecraft movements and ensuring safe docking procedures.

Cluster 2 (Green): Satellite Motion and Navigation Systems: focuses on motion analysis and satellite systems, essential for maintaining satellite operations and avoiding debris in space.

Cluster 3 (Blue): Propulsion and Re-entry Management Systems: highlights innovations in propulsion and re-entry technologies, ensuring that spacecraft can safely navigate through space and re-enter Earth's atmosphere without encountering debris.

Cluster 4 (Yellow): Attitude Control and Vehicle Tracking Systems: is centred on spacecraft orientation and tracking technologies, which are crucial for maintaining proper spacecraft attitude and monitoring movements, particularly in debris-dense orbits.

This visualization reflects France's focused efforts on developing technologies that enhance spacecraft control, navigation, and safety, particularly in environments where space debris poses significant risks. Each cluster shows a specialized area of innovation contributing to the safe and efficient operation of space missions amidst the growing challenge of space debris.

5.2.8 UK

Figure 24: Visualisation of UK IPC Debris Patents Clusters

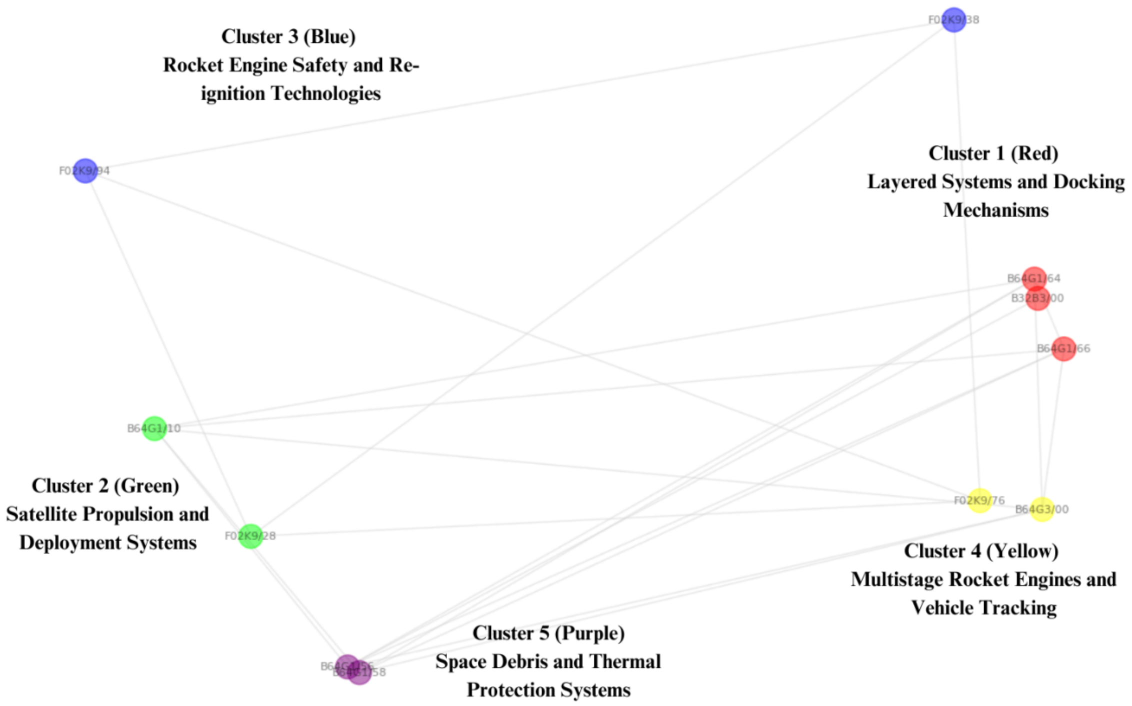


Figure 24 represents the results of the DBSCAN clustering algorithm visualization specific to the UK.

Cluster 1 (Red): Layered Systems and Docking Mechanisms: emphasizes technologies related to layered structural products and docking systems for spacecraft, ensuring the durability and safe docking of vehicles in debris-laden space environments.

Cluster 2 (Green): Satellite Propulsion and Deployment Systems: focuses on artificial satellites and propulsion systems, particularly those utilizing multiple propellant charges, essential for stable satellite operations and propulsion in space.

Cluster 3 (Blue): Rocket Engine Safety and Re-ignition Technologies: deals with rocket engine safety, including re-ignition systems and safety measures to prevent accidental ignition, which are vital for ensuring safe space operations and debris management.

Cluster 4 (Yellow): Multistage Rocket Engines and Vehicle Tracking: highlights the role of multistage rocket engines and tracking systems in propelling and monitoring spacecraft, ensuring efficient propulsion and continuous tracking during space missions.

Cluster 5 (Purple): Space Debris and Thermal Protection Systems: focuses on protection technologies against space debris and extreme temperatures, such as heat shields, crucial for safeguarding spacecraft from external threats.

The visualization reveals the UK's commitment to developing advanced systems for safe spacecraft operations, propulsion, and protection in space environments, with a specific emphasis on mitigating the risks posed by space debris.

5.2.9 Germany

Figure 25: Visualisation of Germany IPC Debris Patents Clusters

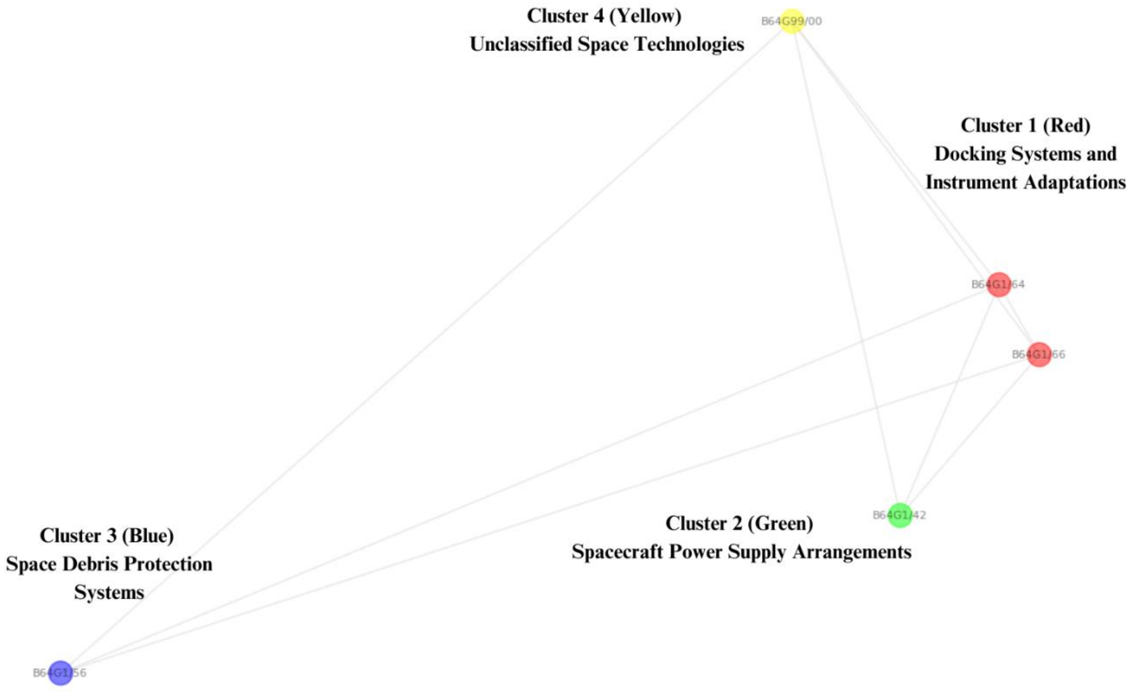


Figure 25 represents the results of the DBSCAN clustering algorithm visualization specific to Germany.

Cluster 1 (Red): Docking Systems and Instrument Adaptations: emphasizes innovations in coupling and separating spacecraft components, particularly docking mechanisms and instrument adaptations, which are essential for spacecraft flexibility and efficiency in debris-filled environments.

Cluster 2 (Green): Spacecraft Power Supply Arrangements: focuses on the power supply system's necessary to ensure reliable and continuous operations for spacecraft, especially in long-duration missions where power stability is crucial for safe manoeuvring and debris avoidance.

Cluster 3 (Blue): Space Debris Protection Systems: highlights the importance of protection technologies designed to shield spacecraft from meteoroid impacts and space debris, playing a vital role in safeguarding the integrity of spacecraft structures.

Cluster 4 (Yellow): Unclassified Space Technologies: includes various cosmonautic innovations that do not fall under traditional classifications but still contribute to spacecraft operations, showcasing Germany's wide-ranging approach to space debris challenges.

This visualization reflects Germany's commitment to enhancing spacecraft safety and operational efficiency in the context of increasing space debris, focusing on docking systems, power supply arrangements, and protection technologies.

5.3 Patent ID DBSCAN

This section provides insight into the individual patent clustering results, unveiling underlying patterns and groups in the patent data. This clustering analysis extends beyond the IPC code based DBSCAN approach by focusing on individual patents, through their display key, rather than just IPC codes. This provides more detailed insights into specific emerging patent technologies. The patent debris have been categorised into three groups, each representing a different aspect of space debris management: prevention, mitigation, and removal, all aimed at reducing the threat of space debris.

5.3.1 All Countries

Figure 26: Visualisation of All Countries Display Key Debris Patents Clusters

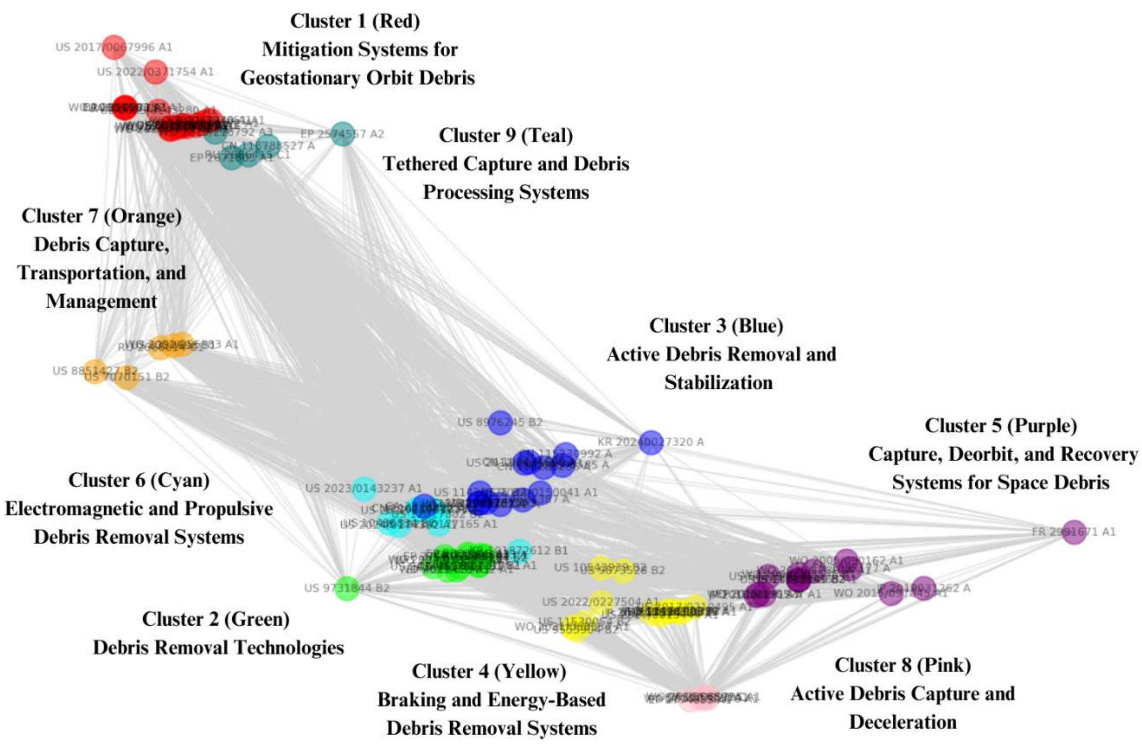


Figure 26 represents the results of the DBSCAN clustering algorithm visualization for all countries.

In Figure 26 there are a total of 82 patents creating 9 clusters and of those 82 patents 28 of those patents do not belong to one of the countries used in our analysis, showcasing the dominance of these main space faring nations. Additionally, of the 28 patents 21 of these do not belong to a specific country as they represent international patent application filed through the WIPO. This leaves three countries with two patents each for South Korea, and Ukraine and three for Canada. Of these patents only two patents, one from Ukraine one from Canada, address mitigation technologies with the rest focusing on removal technologies.

Cluster 1 (Red): Space Debris Tracking and Collision Mitigation Systems: focuses predominantly on mitigation policies for space debris, as highlighted by the various patents aimed at tracking, monitoring, and avoiding collisions with space debris. This cluster encapsulates a wide range of technologies, from sophisticated space traffic management systems to more unconventional patents like space games involving debris tracking. The dense interconnections within the cluster suggest a strong technological focus on tracking and collision avoidance, reflecting a global effort to improve space situational awareness. Many of the patents focus on real-time collision avoidance, improving the accuracy of orbital debris tracking, and managing large satellite constellations to prevent debris-related accidents. This cluster emphasizes the increasing importance of mitigation strategies in space debris management, showing a clear trend towards solutions that minimize the risks posed by space debris in geostationary and lower Earth orbits, especially as satellite mega constellations become more prevalent.

Cluster 2 (Green): Debris Removal Technologies: containing 15 nodes focused exclusively on Debris Removal Technologies. The patents in this cluster all address Removal technologies, highlighting active approaches to capturing and removing space debris from orbit. The various patents propose methods such as electrodynamic tethers, satellite towing devices, harpoons, and spacecraft equipped with interception systems, all designed to actively remove or deorbit debris. This cluster underscores the critical importance of reducing space debris through direct removal techniques to prevent collisions and maintain a safe orbital environment. The dense connectivity between patents in this cluster suggests strong interrelations in terms of technology and innovation, with a clear focus on physical debris removal solutions that tackle the growing problem of space debris in Earth's orbit. This highlights the global effort in advancing technologies that ensure safer and more sustainable space operations.

Cluster 3 (Blue): Active Debris Removal and Stabilization: consists of 15 nodes and is focused on ADR and Stabilization. The patents within this cluster primarily address technologies aimed at actively removing space debris and stabilizing unstable objects in orbit. A significant portion of these technologies involves systems that use magnetic or electromagnetic forces to deorbit debris, along with devices for tracking and stabilizing debris to prevent collisions. Additionally, some patents focus on mitigation strategies, such as monitoring debris using satellite systems or protective mechanisms like spacecraft shields to prevent damage from space debris. This cluster emphasizes both active removal and mitigation, reflecting a comprehensive approach to managing space debris by stabilizing and removing it, as well as protecting operational spacecraft. The interconnectedness within the cluster suggests a strong technological focus on improving the safety of space environments through debris removal and stabilization. This reflects the growing importance of developing robust systems to deal with both existing and potential space debris hazards.

Cluster 4 (Yellow): Braking and Energy-Based Debris Removal Systems: comprises of 14 patents, each focusing on various innovative technologies aimed at debris removal, including braking mechanisms, electromagnetic wave systems, and mitigation strategies involving satellite stability and debris collection. The patents in this cluster highlight both removal and mitigation policies, showing a strong emphasis on controlled, efficient, and energy-based solutions for reducing orbital debris. The dense network of nodes and edges within the yellow cluster indicates significant interconnectivity between the patents, implying a shared technological focus on debris removal and spacecraft safety. This cluster offers valuable insight into how multiple countries, particularly the US and Japan, are prioritizing the development of technologies that address the pressing issue of space debris, utilizing braking force, electromagnetic waves, and tethering systems for both large and small debris management.

Cluster 5 (Purple): Capture, Deorbit, and Recovery Systems for Space Debris: reveals a collection of patents that address space debris removal using a variety of technologies, such as tethers, electromagnetic systems, and mechanical capture devices, along with innovative disposal methods like burning debris during re-entry or recovering it for reuse. These systems offer both passive and active strategies for dealing with space debris, emphasizing methods that ensure safe re-entry or disposal of debris in Earth's atmosphere, or in some cases, even ejecting it to interplanetary space. The patents reflect a clear alignment with both removal and disposal policies, with an emphasis on reducing long-term risks in Earth's orbit. The dense interconnections in this cluster suggest a high degree of technological overlap and focus on innovative mechanisms for debris capture and mitigation, illustrating the global push toward safer orbital environments and sustainable space practices.

Cluster 6 (Cyan): Electromagnetic and Propulsive Debris Removal Systems: is significant because it reveals a strong emphasis on advanced technologies, such as electromagnetic and propulsion systems, for space debris removal and satellite constellation management. These technologies aim not only at capturing and deorbiting space debris but also at preventing debris generation by controlling satellite formations and ensuring safe orbital transfers. The breakdown of patents includes innovative systems like electromagnetic debris collectors, self-consuming CubeSats, and satellites designed for debris detection and observation. This cluster demonstrates how countries like the US, China, and Korea are developing cutting-edge solutions to mitigate space debris risks, reflecting a global concern about maintaining orbital safety through active removal and strategic mitigation efforts. The interconnections between the patents suggest a strong technical overlap and collaboration in debris-related technologies.

Cluster 7 (Orange): Active Debris Capture and Deceleration: focuses on Active Debris Capture and Deceleration technologies, with patents that specifically address the removal technologies. This cluster includes patents that outline methods for capturing large and tumbling debris using harpoon-based mechanisms, adhesive units, and braking systems designed to decelerate debris in specific orbital regions. The technologies in this cluster aim to actively remove debris by altering its orbit and reducing its velocity, preventing further accumulation and potential collisions in space. The close interconnections between the patents in this cluster suggest a strong focus on developing systems for capturing unstable debris and applying deceleration techniques for safe removal from orbit. This highlights a concentrated global effort on tackling the challenge of large debris management, with a specific emphasis on deceleration and stabilization techniques for effective debris removal.

Cluster 8 (Pink): Debris Capture, Transportation, and Management: contains patents focused on Debris Capture, Transportation, and Management systems. The technologies within this cluster highlight a combination of removal and mitigation strategies for managing space debris. Patents in this cluster describe methods such as net-based systems for capturing debris, nuclear-powered space tugs for transporting and recovering debris, and spacecraft dispensers that minimize debris creation by optimizing spacecraft configurations. The patents emphasize both ADR through capture and retrieval mechanisms and mitigation by reducing the generation of new debris during spacecraft launches. This cluster's interconnected nodes indicate a strong focus on innovative solutions for maintaining a cleaner and safer orbital environment, ensuring that both debris prevention and active removal techniques are employed to handle the growing issue of space debris.

Cluster 9 (Teal): Tethered Capture and Debris Processing Systems: focuses on Tethered Capture and Debris Processing Systems for space debris removal, as illustrated by the five patents in this group. These technologies highlight innovative methods such as tethered systems, net-based debris capture, and the creation of artificial atmospheres to deorbit or recycle space debris. Several patents in this cluster describe systems that not only capture debris but also convert it into usable resources, such as fuel for spacecraft engines, indicating a dual-purpose approach to both debris removal and resource generation. Additionally, the cluster includes stabilization techniques for managing debris during the removal process, mitigating the risk of collisions and ensuring safer operations. The close connections between the patents in this cluster suggest a concerted effort to develop comprehensive, multifunctional systems for capturing, processing, and deorbiting space debris, reflecting a strong focus on sustainable debris management solutions.

5.3.2 *EU*

Figure 27: Visualisation of European Union Display Key Debris Patents Clusters

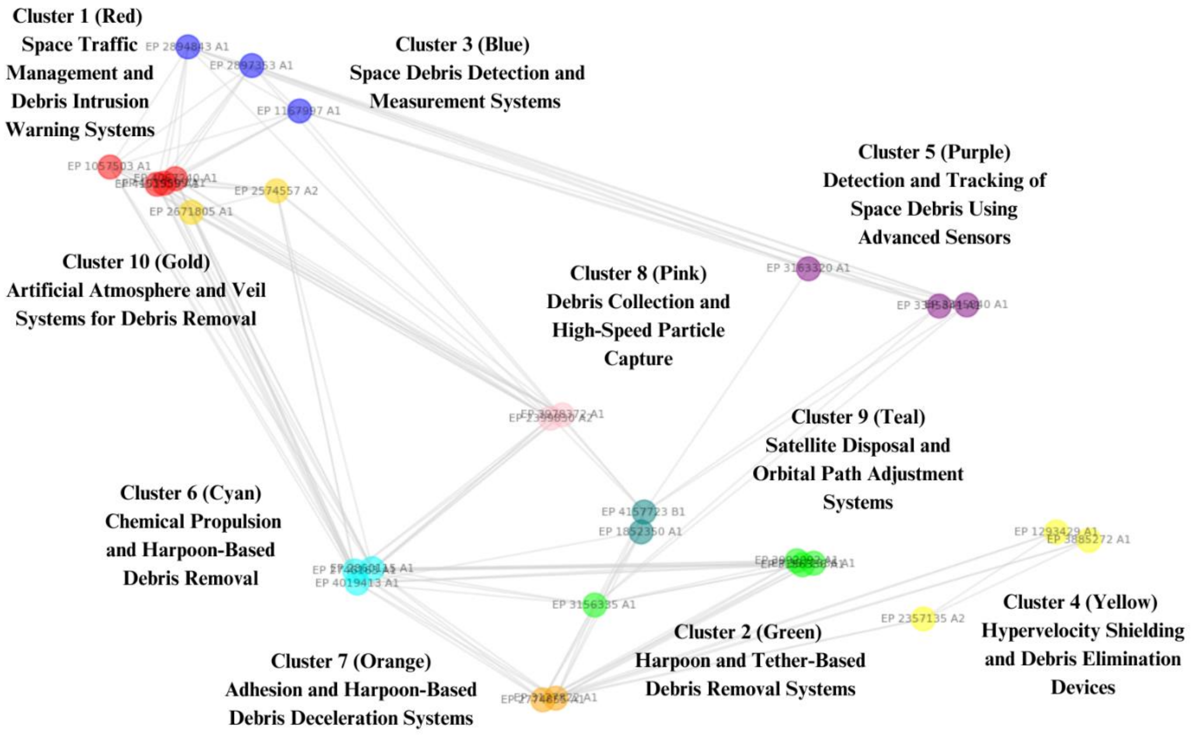


Figure 27 represents the results of the DBSCAN clustering algorithm visualization for all countries.

Cluster 1 (Red): Space Traffic Management and Debris Intrusion Warning Systems: focuses on Space Traffic Management and Debris Intrusion Warning Systems. The four patents in this cluster primarily address mitigation policies related to managing space debris and preventing collisions in orbit. These patents propose systems for recording and analysing space object data, predicting potential orbital interactions, and generating warnings for imminent debris collisions. The patents aim to provide timely information that helps operators avoid hazards by sharing space object information and performing danger analysis. This cluster highlights the critical role of space traffic management in mitigating debris-related risks, ensuring safer operations in increasingly crowded orbits. The strong connections between the patents suggest a well-integrated approach to managing and mitigating space debris threats through enhanced situational awareness and predictive analytics.

Cluster 2 (Green): Hypervelocity Shielding and Debris Elimination Devices: focuses on Harpoon and Tether-Based Debris Removal Systems, with four patents addressing the removal technologies. These patents describe various methods for capturing and removing space debris using harpoons and tethers. One system utilizes an electroconductive tether to lower the orbit of debris for eventual re-entry, while others employ harpoons to secure debris for controlled descent. Another approach involves coordinated satellite systems using tethers and harpoons to jointly capture and guide debris. These technologies emphasize ADR through direct capture and descent control, reducing the risk of collisions by safely deorbiting debris. The interconnectedness of the patents within the cluster highlights a cohesive technological approach to addressing space debris using tethered and harpoon-based capture methods, showcasing the focus on innovative, hands-on removal strategies.

Cluster 3 (Blue): Space Debris Detection and Measurement Systems: focuses on Space Debris Detection and Measurement Systems, with three patents addressing mitigation technologies through debris detection and measurement technologies. The patents describe methods for identifying and measuring space debris using innovative techniques such as pixel thresholding, laser-based measurements, and image stacking. These methods enable the detection of debris by analysing pixel values in images or using laser beams to determine the size and location of debris in space. The technologies in this cluster aim to mitigate potential collision risks by accurately detecting and classifying space debris, thereby supporting efforts to track and manage debris in Earth's orbit. The interconnectedness of these patents shows a shared focus on improving debris detection capabilities, which is crucial for preventing collisions and maintaining safer space operations.

Cluster 4 (Yellow): Hypervelocity Shielding and Debris Elimination Devices: focuses on Hypervelocity Shielding and Debris Elimination Devices. The three patents in this cluster address mitigation technologies, particularly through the development of shielding technologies that protect spacecraft from the harmful effects of high-speed space debris. One patent introduces a multilayer hypervelocity impact shield that disperses debris on impact, while another presents a micrometeoroid and orbital debris shield designed to prevent penetration from high-velocity objects. The third patent describes a device that breaks apart on impact, eliminating debris by absorbing its energy. This cluster reflects a strong focus on supporting technologies for mitigating the effects of space debris, ensuring spacecraft safety by minimizing the risk of damage from high-speed debris impacts. The interconnectivity of these patents highlights a shared objective of improving spacecraft resilience to debris-related hazards.

Cluster 5 (Purple): Detection and Tracking of Space Debris Using Advanced Sensors: focuses on Detection and Tracking of Space Debris Using Advanced Sensors. The three patents in this cluster address both mitigation and removal policies. Two of the patents involve sensor systems using antennas to detect space debris, measure its size and impact force, and classify its potential threat. These systems contribute to mitigating debris risks by providing real-time data on debris characteristics, enabling operators to track and avoid collisions. The third patent introduces a laser-based system designed to track and vaporize debris, directly addressing removal by eliminating debris from orbit. This cluster highlights a strong technological focus on advanced sensing and detection technologies that play a crucial role in both preventing and addressing the hazards posed by space debris. The interconnections within this cluster suggest a shared emphasis on using cutting-edge sensor and laser systems to enhance space safety through effective debris detection and removal.

Cluster 6 (Cyan): Chemical Propulsion and Harpoon-Based Debris Removal: focuses on Chemical Propulsion and Harpoon-Based Debris Removal systems, with three patents addressing the removal technologies. These technologies aim to capture and remove space debris using a combination of chemical propulsion systems and harpoon-based capture devices. One patent outlines a satellite equipped with chemical propulsion that captures debris at high altitudes, preventing it from entering congested orbital regions. Another patent describes a method where spacecraft attach to uncontrolled debris and move it into a safer orbit. The third patent focuses on a harpoon-based system that captures and removes debris using a telescopic mast. The patents in this cluster represent a multifaceted approach to ADR, combining propulsion systems for manoeuvrability with harpoon technologies for precise debris capture. The interconnections between these patents suggest an integrated strategy to manage space debris through innovative capture and removal techniques.

Cluster 7 (Orange): Adhesion and Harpoon-Based Debris Deceleration Systems: focuses on Adhesion and Harpoon-Based Debris Deceleration Systems, with two patents addressing the removal policy. These patents propose systems designed to capture and decelerate space debris using adhesion mechanisms and harpoon-based devices. One patent describes a debris removal device that applies braking forces after capturing debris via adhesion, slowing its orbit and guiding it to safe disposal. The second patent involves using a harpoon to capture tumbling debris, with a deceleration system that prevents further collisions by controlling the debris' speed. The technologies in this cluster aim to actively remove space debris by ensuring its safe and controlled descent through innovative capture and braking methods. The strong interconnections suggest a shared focus on debris deceleration as a key element in debris management and removal strategies.

Cluster 8 (Pink): Debris Collection and High-Speed Particle Capture: focuses on Debris Collection and High-Speed Particle Capture, with two patents addressing both removal and mitigation technologies. The first patent presents a system for forming satellite constellations that also functions to collect and deorbit space debris, contributing to the active removal of debris from orbit. The second patent involves a device designed to capture high-speed debris particles, absorbing their impact to prevent further collisions, thus playing a key role in mitigating space debris risks. This cluster highlights complementary technologies aimed at both removing large debris and capturing smaller high-speed particles, reducing the overall risk of collisions in space. The patents' interconnectedness underscores the importance of integrated approaches to managing and mitigating space debris through both collection and impact absorption technologies.

Cluster 9 (Teal): Satellite Disposal and Orbital Path Adjustment Systems: focuses on Satellite Disposal and Orbital Path Adjustment Systems, with two patents addressing both disposal and mitigation policies. The first patent outlines a method for safely disposing of geostationary satellites at the end of their operational life by moving them to a graveyard orbit, thus preventing the generation of space debris. The second patent describes a method for adjusting satellite orbits to avoid collisions with space debris or other satellites, mitigating potential risks. This cluster highlights the importance of both safe satellite disposal and proactive orbital adjustments as key strategies to prevent future debris accumulation and avoid collisions, ensuring safer and more sustainable satellite operations in Earth's increasingly congested orbits. The connections between the patents emphasize the close relationship between orbital management and debris prevention.

Cluster 10 (Gold): Artificial Atmosphere and Veil Systems for Debris Removal: focuses on Artificial Atmosphere and Veil Systems for Debris Removal, with two patents addressing the removal policy. The patents propose innovative methods to actively remove space debris from orbit. One patent discusses creating an artificial atmosphere that generates drag on debris, slowing it down and guiding it toward a lower orbit for re-entry and destruction. The second patent introduces a veil-based system that captures debris and uses tensile forces to remove it from orbit. Both systems represent ADR technologies aimed at reducing orbital clutter and minimizing collision risks. This cluster reflects a focused effort on developing advanced mechanisms for debris capture and deceleration, contributing to the broader goal of maintaining safer and cleaner space environments. The strong connectivity between these patents indicates a shared focus on direct debris removal through physical intervention.

5.3.3 USA

Figure 28: Visualisation of USA Display Key Debris Patents Clusters

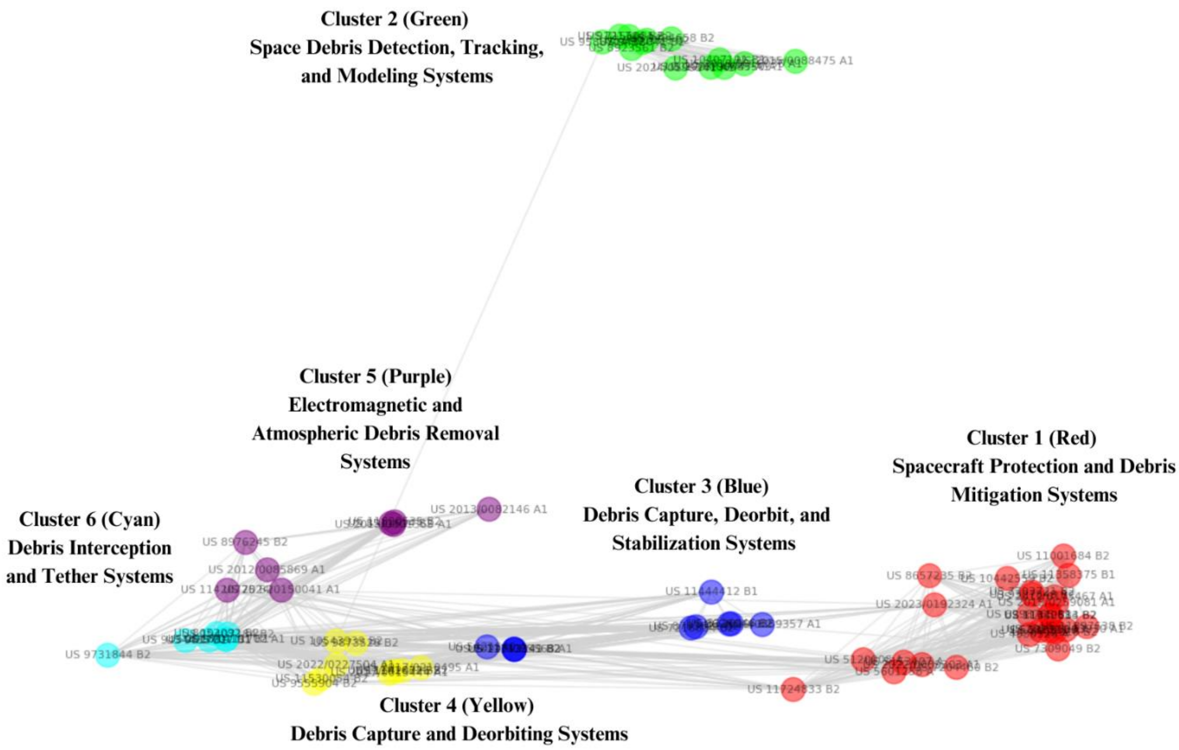


Figure 28 represents the results of the DBSCAN clustering algorithm visualization for all countries.

Cluster 1 (Red): Debris Interception and Tether Systems: focuses on Spacecraft Protection and Debris Mitigation Systems. This cluster, consisting of 25 patents, addresses technologies designed to protect spacecraft from micrometeoroids and orbital debris using shielding systems, impact-resistant materials, and innovative debris mitigation techniques. The patents range from multi-layer particle shields and self-healing polymers to systems that use radiation and tethers to either protect spacecraft or remove debris from orbit. The cluster is positioned tightly in the centre-right of the image, indicating strong connectivity between the patents and the shared objective of enhancing spacecraft resilience and debris mitigation strategies. This close clustering highlights the significant focus within this technological domain on both protection and mitigation policies, demonstrating the critical need for robust systems to safeguard space assets from the ever-growing issue of space debris.

Cluster 2 (Green): Space Debris Detection, Tracking, and Modelling Systems: focuses on Space Debris Detection, Tracking, and Modelling Systems, with 13 patents addressing the mitigation policy. This cluster's relatively isolated position indicates its specialized role in enhancing debris detection and tracking rather than directly engaging in debris removal or physical mitigation efforts seen in other clusters. The patents in this group cover a wide range of technologies aimed at improving our understanding and management of space debris. These include laser-based detection systems, 3D visualization models, and pixel evaluation techniques that are designed to detect even small and faint debris. Several patents also introduce real-time orbital determination systems and optical surveillance technologies, which allow for continuous monitoring and accurate tracking of debris. Additionally, the cluster includes modelling systems that simulate long-term debris behaviour, collisions, and debris generation, improving predictions and risk assessments. The close interconnections within this cluster suggest a shared focus on using advanced detection and modelling technologies to mitigate debris-related risks by providing crucial data on debris movement and behaviour. By enhancing the precision and effectiveness of debris tracking, this cluster supports efforts to reduce the risk of collisions in space. Its technologies are foundational to space safety efforts, providing essential information that enables more active mitigation and removal strategies in other clusters. The placement of this cluster highlights the critical role of accurate tracking and prediction systems as a backbone for informed decision-making in space debris management.

Cluster 3 (Blue): Debris Capture, Deorbit, and Stabilization Systems: focuses on Debris Capture, Deorbit, and Stabilization Systems, with 10 patents centred around removal and mitigation technologies. These patents introduce various methods for capturing and stabilizing space debris, including harpoon-based systems, tape spring mechanisms, and nuclear-powered space tugs. The technologies address both ADR—by capturing and deorbiting objects—and mitigation, focusing on stabilizing unstable debris to prevent further hazards. Positioned prominently in the center-left of the visualization, this cluster shows strong interconnectivity between patents, reflecting their shared goal of addressing space debris risks. The diverse range of systems in this cluster highlights ongoing efforts to develop practical solutions for maintaining the safety and sustainability of orbital environments by focusing on both preventing debris instability and actively removing hazardous objects from space.

Cluster 4 (Yellow): Debris Capture and Deorbiting Systems: focuses on Debris Capture and Deorbiting Systems with nine patents addressing the removal policy. The technologies in this cluster offer a range of methods for capturing and removing space debris, such as using adhesion, braking mechanisms, tethers, and electromagnetic systems. These patents aim to remove debris by capturing it and decelerating or deorbiting it efficiently. Systems like polar cusp plasma flux or electromagnetic wave removal focus on leveraging environmental forces to remove smaller debris, while other patents describe multi-object rendezvous systems for larger debris. Interestingly, some methods, such as gossamer apparatus or rotation suppression devices, are designed to handle complex debris scenarios like tumbling or high-speed fragments. The cluster's central position in the visualization suggests strong interconnectivity between its patents and other clusters, highlighting the shared objective of ADR to maintain orbital sustainability. This cluster is key to future efforts in minimizing space debris, addressing both large debris objects and smaller, harder-to-track fragments through innovative deorbiting techniques.

Cluster 5 (Purple): Electromagnetic and Atmospheric Debris Removal Systems: focuses on Electromagnetic and Atmospheric Debris Removal Systems, with eight patents targeting removal, mitigation, and monitoring of space debris. These technologies leverage advanced methods such as magnetic fields, plasma, artificial atmospheres, and drag devices to influence debris trajectory, hasten orbital decay, or actively remove objects from orbit. Patents like US 2012/0085869 A1 and US 2013/0082146 A1 highlight systems that alter debris orbits using electric fields and artificial atmospheres, while others focus on monitoring and detecting debris, such as the optical orbital debris spotter (US 8976245 B2). Positioned centrally and connected to other clusters in the visualization, this cluster underscores the synergy between removal and mitigation efforts, emphasizing the shared goal of reducing debris presence through continuous monitoring and active removal strategies. This strong interconnectivity reflects the innovation and collaboration required to tackle the complex challenge of space debris management.

Cluster 6 (Cyan): Debris Interception and Tether Systems: focuses on Debris Interception and Tether Systems, with seven patents addressing the removal policy. The technologies within this cluster revolve around innovative methods for actively capturing and removing space debris using interception vehicles, tethers, and harpoon-based systems. Notably, several patents introduce orbital debris interception vehicles equipped with Whipple shields for intercepting debris, while other methods involve micro vehicles, modular systems, and tethering mechanisms to capture and control the debris. The central theme in this cluster is the use of modular and reconfigurable systems to intercept and manoeuvre debris, thereby aiding in its removal from orbit. The position of this cluster in the visualization suggests it is relatively self-contained, showing strong internal connectivity, which indicates that the patents in this cluster share common principles and methods in debris capture and interception techniques. This cluster highlights the growing emphasis on active removal systems to ensure space sustainability through advanced, mechanical-based debris management solutions.

5.3.4 China

Figure 29:Visualisation of China Display Key Debris Patents Clusters

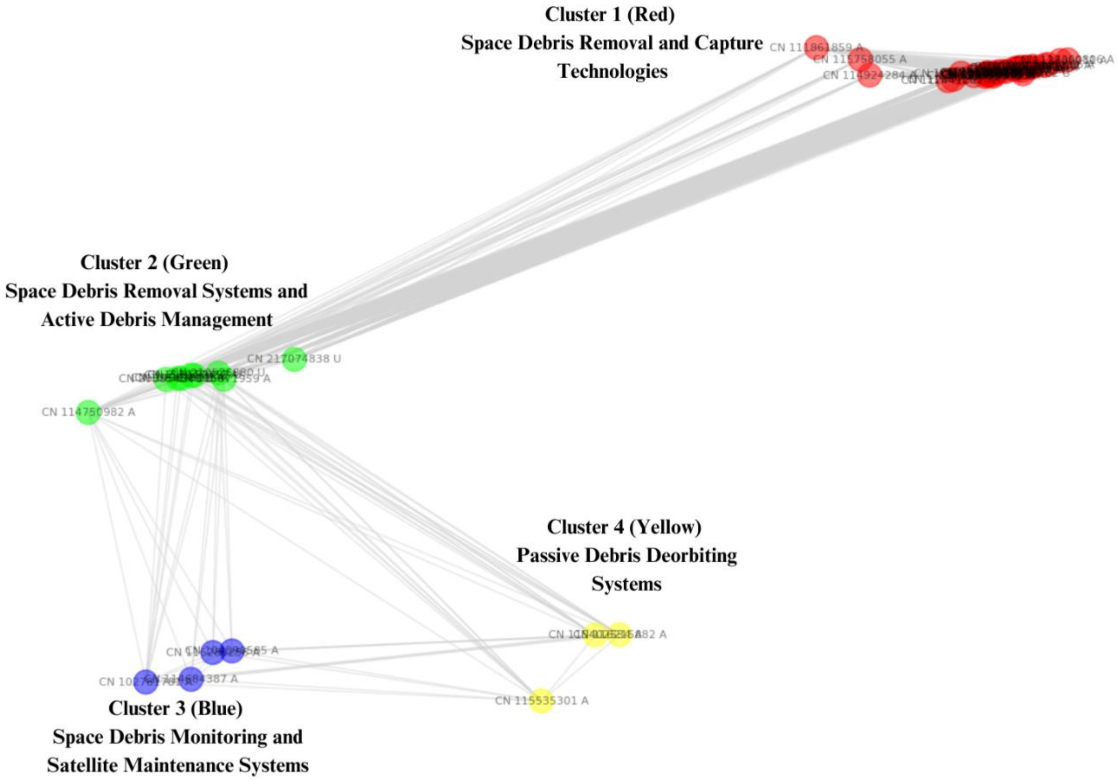


Figure 29 represents the results of the DBSCAN clustering algorithm visualization for all countries.

Cluster 1 (Red): Space Debris Removal and Capture Technologies: focused on Space Debris Removal and Capture Technologies in China. The cluster is visually distinct from others in the graph, positioned in the upper right and densely connected, indicating a robust interaction among the patents. Most technologies in this cluster, 23 patents, revolve around removal methods, using tools like lasers, mechanical arms, nets, and projectiles to capture and deorbit debris. Some patents focus on laser-based debris removal, while others, focus on mechanical arms for active debris capture. Additionally, there are 6 patents addressing monitoring systems to track and predict debris movements, utilizing satellite formations and laser-guided tracking, and 3 patents focusing on prevention, such as the rope net system, aimed at capturing debris to prevent further fragmentation. The dense interconnectivity and strong focus on removal solutions illustrate the emphasis on actively tackling debris accumulation, with several patents working towards improving capture precision and efficiency to prevent future debris-related hazards.

Cluster 2 (Green): Space Debris Removal Systems and Active Debris Management: positioned in the middle-left section of the visualization, highlights 9 patents focused on Space Debris Removal Systems and Active Debris Management. The majority of these patents, 7, address removal technologies, which employs a rocket tail stage to capture debris while in orbit or another patent that uses a solar-powered device for debris captures and removal. Flexible structures are a common theme, which utilizes flexible film arms for capturing and dragging debris, as well as patents which features flexible wrist mechanisms for capturing debris. One patent, focuses on monitoring, using an air-cushion-based device for debris tracking and catching. Another patent, tackles prevention by stabilizing debris with resistance sails, reducing the risk of future collisions. This cluster demonstrates a strong emphasis on flexible and solar-powered systems for debris capture, underlining China's innovations in sustainable debris management technologies. The cluster's central position in the visualization suggests its connection to broader debris management themes, linking removal, monitoring, and prevention. This is especially important considering it is the bridge between cluster 1 with cluster 2 and 3.

Cluster 3 (Blue): Space Debris Monitoring and Satellite Maintenance Systems: consists of 4 patents related to Space Debris Monitoring and Satellite Maintenance Systems. Positioned in the lower left part of the image, this cluster shows a clear focus on the monitoring and prevention of space debris. Three of the patents address monitoring technologies, stabilizes and alters the orbits of unstable debris, with another patent involving a micro-nano satellite for tracking space debris in near-Earth orbits. One patent offers a system for in-orbit satellite maintenance and debris tracking, ensuring satellites' operational safety. Another patent focuses on prevention, detailing a reusable cargo aircraft designed to avoid space debris damage. The placement of this cluster, slightly isolated from others, underscores its niche role in debris monitoring and satellite maintenance, contrasting with more removal-focused clusters in the visualization. This indicates that while ADR is a major area of focus, monitoring and preventing debris damage remain crucial support strategies.

Cluster 4 (Yellow): Passive Debris Deorbiting Systems: situated in the bottom-middle of the visualization, focuses on Passive Debris Deorbiting Systems with 3 patents addressing removal technologies. These technologies emphasize passive methods to aid in deorbiting space debris, using structures that increase drag. For example, one patent describes a deorbiting ball that inflates to increase air resistance, helping debris naturally re-enter the atmosphere. Similarly, there is another patent that employs a resistance sail to passively deorbit spacecraft by enhancing drag. A final patent introduces a spacecraft system designed for actively collecting debris while providing protection during the deorbiting process. This cluster highlights China's commitment to using passive systems to reduce debris in orbit by leveraging the natural forces of drag, offering low-energy, sustainable debris management solutions. The relative isolation of this cluster indicates a specialized focus on passive deorbiting techniques within the broader context of debris removal technologies.

5.3.5 Japan

Figure 30: Visualisation of Japan Display Key Debris Patents Clusters

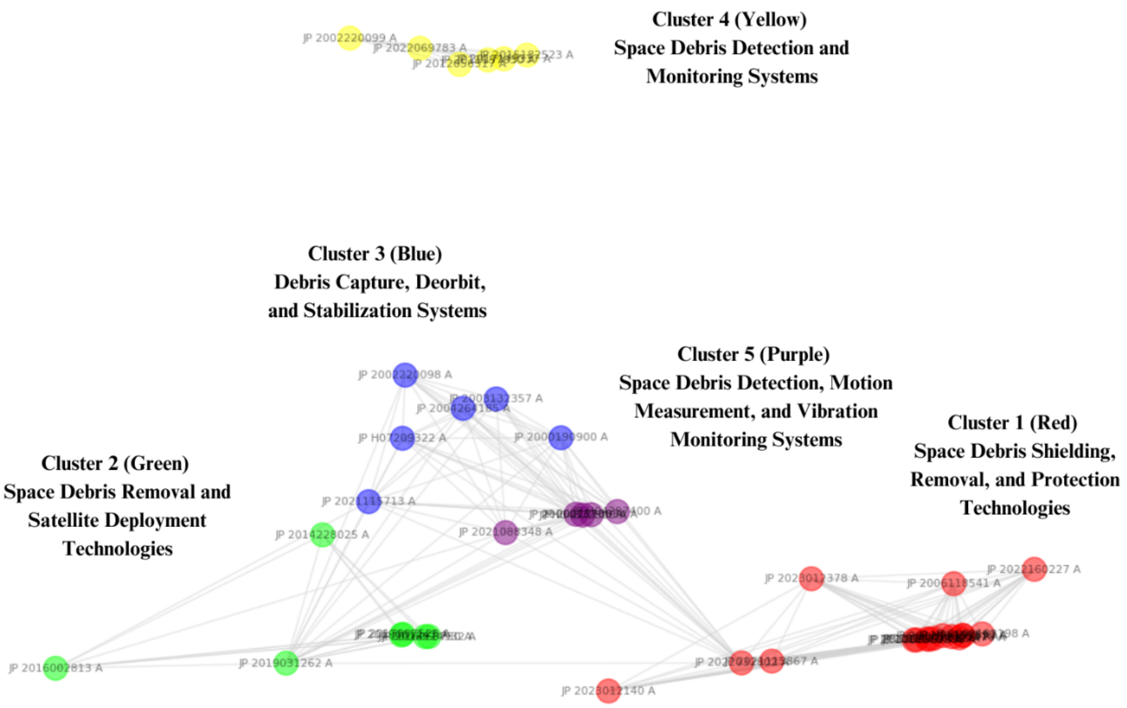


Figure 30 represents the results of the DBSCAN clustering algorithm visualization for all countries.

Cluster 1 (Red): Space Debris Shielding, Removal, and Protection Technologies: focuses on Space Debris Shielding, Removal, and Protection Technologies, with 17 patents addressing Prevention and Removal Policies. The technologies in this cluster are designed to protect spacecraft from debris impacts and actively remove debris from orbit. The patents describe innovations such as pressurized panel structures, multilayer shields, tethered satellite systems for debris capture, and methods for decelerating debris to ensure atmospheric burn-up. Many of these systems aim to enhance spacecraft durability against impacts through advanced shielding materials like ceramic sintered bodies and aluminium-clad plates, while others focus on actively reducing the debris load by capturing or destroying debris. The strong interconnections between the patents in this cluster suggest a shared goal of ensuring spacecraft safety through both passive protection and active debris management. The prominent placement of this cluster in the visualization indicates its importance in comprehensive debris mitigation strategies.

Cluster 2 (Green): Space Debris Removal and Satellite Deployment Technologies: located toward the lower left of the visualization, focuses on Space Debris Removal and Satellite Deployment Technologies, consisting of seven patents. These technologies centre around methods for capturing and removing space debris, as well as deploying satellites in a way that minimizes debris generation. Positioned within the broader network, this cluster demonstrates its relevance through strong connections to adjacent clusters, suggesting its technologies play a critical role in both ADR and preventing future debris during satellite missions. The patents within this cluster highlight innovations like harpoon-based debris capture systems, tether mechanisms to deorbit debris, and spacecraft designed to deploy satellites without generating additional debris. The placement of this cluster reflects the importance of integrating removal and prevention technologies to ensure sustainable space operations, bridging the gap between debris capture systems and deployment strategies aimed at reducing space debris.

Cluster 3 (Blue): Space Debris Detection, Motion Measurement, and Vibration Monitoring Systems: positioned toward the centre of the visualization, and focuses on Space Debris Detection, Motion Measurement, and Vibration Monitoring Systems. The six patents within this cluster address technologies that track debris, measure its motion, and detect vibrations caused by collisions. Positioned with moderate connections to other clusters, it highlights the critical role of monitoring in space debris management. These technologies utilize imaging, sensors, and data processing to measure the position and movement of debris, offering methods like triangulation and vibration detection for monitoring collisions in microgravity environments. This cluster's position reflects its foundational relevance in mitigation policy by providing essential data to track, monitor, and assess debris, which is vital for preventing collisions and ensuring the long-term sustainability of space activities. Its moderate connectivity indicates that monitoring systems, while distinct, are closely tied to broader debris management strategies across other clusters.

Cluster 4 (Yellow): Space Debris Detection and Monitoring Systems: located in the top of the visualization, focuses on Space Debris Detection and Monitoring Systems, with six patents addressing technologies related to tracking and observing debris using imaging, laser, and radar techniques. Positioned slightly isolated from other clusters, it emphasizes the specialized nature of monitoring systems, which are foundational for mitigating debris risks. The patents cover methods such as laser observation systems, photographic debris detection, and radar-based tracking, highlighting innovations aimed at improving the accuracy and reliability of debris monitoring. This cluster's strategic position in the visualization reflects its distinct role in providing essential tools for ongoing observation and mitigation efforts, crucial for preventing collisions and ensuring the safety of space operations. The notable isolation of this cluster, with no visible links to other groups, suggests that the patents within it are highly specialized and distinct from the ADR or mitigation systems seen in other clusters. This separation could be due to the passive, observational nature of the technologies in Cluster 4, which primarily focus on tracking and monitoring rather than on the mechanical or structural approaches used for debris capture or shielding. This division highlights the different roles these technologies play in space debris management strategies, where monitoring systems provide critical data to support more active intervention methods.

Cluster 5 (Purple): Space Debris Detection and Collision Assessment Technologies: focuses on Space Debris Detection and Collision Assessment Technologies, with five patents addressing various Monitoring Policies. This cluster represents advancements in methods for detecting and assessing collisions with space debris. The patents range from using optical detectors and thermal sensors to monitor debris movement and collisions, to methods involving laser beams and vibration sensors to assess impacts on spacecraft. The technologies described enhance safety by providing real-time monitoring of space debris and impact detection, enabling proactive measures to prevent damage. The cluster’s central position in the visualization, with strong connections to other nodes, highlights its integral role in monitoring and tracking debris, a critical component of space debris management. These technologies reflect Japan’s commitment to improving the monitoring and detection of space debris to mitigate collision risks and ensure space safety.

5.3.6 Russian Federation

Figure 31: Visualisation of Russia Display Key Debris Patents Clusters

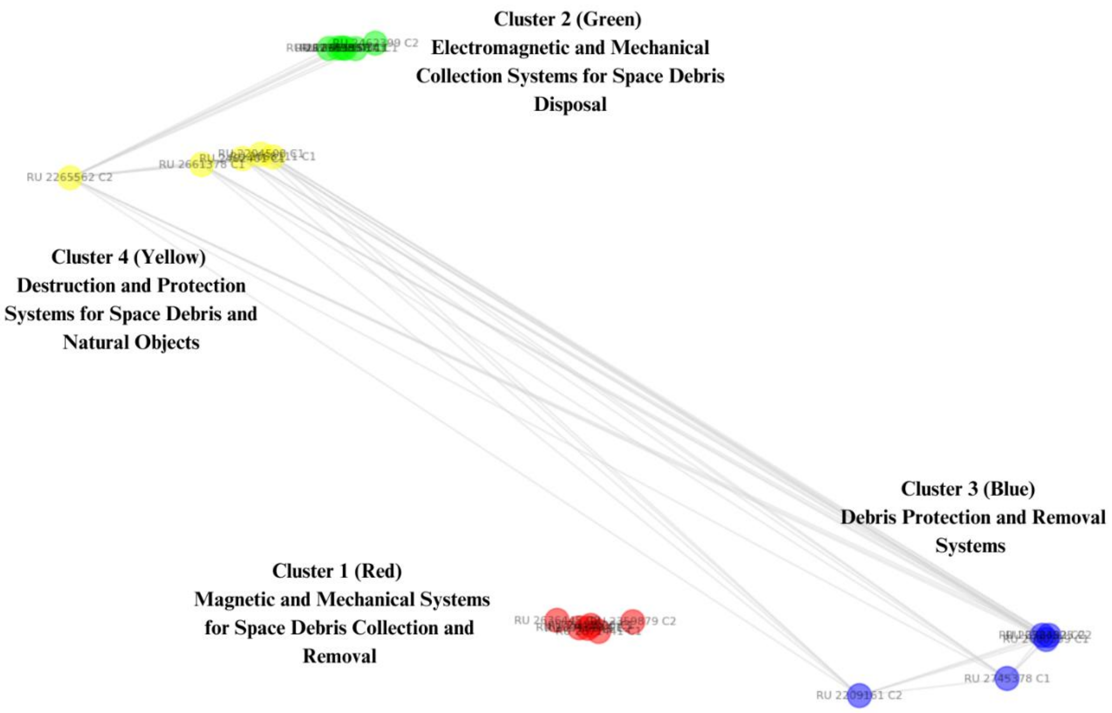


Figure 31 represents the results of the DBSCAN clustering algorithm visualization for all countries.

Cluster 1 (Red): Magnetic and Mechanical Systems for Space Debris Collection and Removal: positioned in the lower section of the visualization, focuses on Magnetic and Mechanical Systems for Space Debris Collection and Removal. This cluster consists of six patents that address both removal and mitigation policies through innovative technologies like magnets, harpoons, docking systems, and decomposing materials. These systems aim to actively capture, control, and remove debris from space. The use of magnetic fields, adhesive means, and autonomous docking modules emphasizes an engineering-focused approach to debris management. The cluster's position, isolated from other clusters but with several interconnecting links, reflects the specialized nature of these mechanical solutions and their importance in physical debris removal and handling. These technologies play a crucial role in reducing space debris risks by addressing the active capture and prevention of debris accumulation. The relative isolation of the cluster may highlight the niche but critical role of such hardware-based debris removal systems in the broader context of space debris management strategies.

Cluster 2 (Green): Electromagnetic and Mechanical Collection Systems for Space Debris Disposal: positioned in the upper-left quadrant of the visualization, focuses on Electromagnetic and Mechanical Collection Systems for Space Debris Disposal. It contains six patents that emphasize the use of electromagnetic fields, braking elements, and mechanical systems such as nets and tethers to capture, collect, and remove space debris. The cluster highlights innovative methods for decelerating debris, transporting it to disposal orbits, and recycling large debris pieces. This cluster's relevance lies in its emphasis on non-contact collection systems, which use electromagnetic forces to capture and control debris, as well as methods that involve towing or slowing debris to guide it into lower orbits for safe disposal. The relatively isolated but connected position in the visualization suggests that these technologies are highly specialized, primarily focusing on removal strategies without direct overlap with other debris management clusters, such as shielding or protection systems. This separation underlines the critical role of these technologies in the active removal of debris to reduce the growing clutter in space.

Cluster 3 (Blue): Debris Protection and Removal Systems: located toward the lower-right of the visualization, focuses on Debris Protection and Removal Systems. The patents within this cluster centre around protecting spacecraft from high-speed space debris and various methods for removing debris from geocentric orbits. This includes shielding technologies designed to deflect debris, systems to transport and move debris for removal, and methods for altering the trajectory of potentially hazardous space objects. The position of this cluster, with strong connections to other clusters, suggests that the technologies it covers are highly integrative, functioning at the intersection of protection and removal strategies. Its relevance lies in combining defensive and active measures, ensuring spacecraft are protected from impacts while also facilitating the removal of debris, thus contributing to both immediate protection and long-term debris reduction in space.

Cluster 4 (Yellow): Space Debris Detection and Monitoring Systems: located toward the upper-left part of the visualization, focuses on Destruction and Protection Systems for Space Debris and Natural Objects. This cluster's patents revolve around methods for breaking debris into smaller fragments, such as using explosives, and providing protective shields for spacecraft, including innovative solutions like using water ice. The cluster is connected to a broader network, indicating that its technologies, though focused on destruction and protection, may integrate with more general debris removal and mitigation efforts. The relevance of this cluster lies in its focus on both destruction of large, potentially hazardous space objects like asteroids and space debris, and in providing protective measures for spacecraft, offering a dual approach of prevention and active intervention in space debris management.

5.3.7 France

Figure 32: Visualisation of France Display Key Debris Patents Clusters

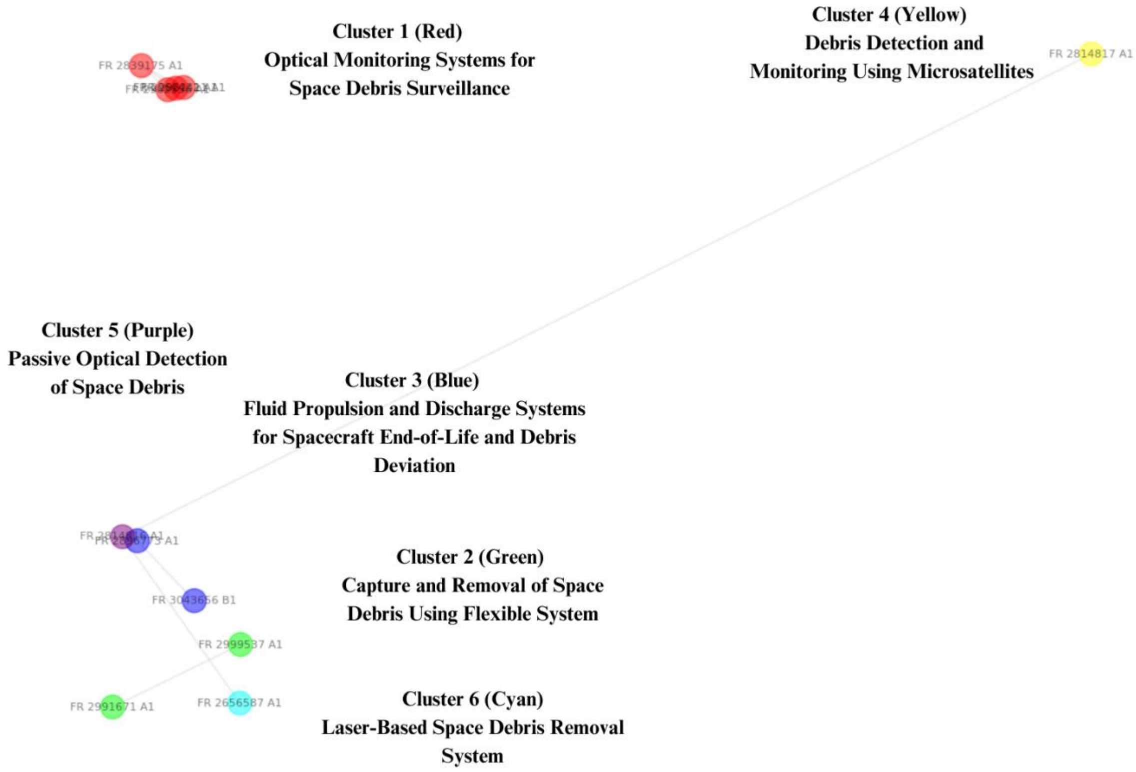


Figure 32 represents the results of the DBSCAN clustering algorithm visualization for all countries.

Cluster 1 (Red): Optical Monitoring Systems for Space Debris Surveillance: located in the upper left of the visualization, focuses on Optical Monitoring Systems for Space Debris Surveillance. The cluster includes patents centred on optical telescopes and imaging technologies used for tracking space debris, particularly in LEO. The key technologies involve global networks of optical stations, telescope-based monitoring systems, and image processing techniques to ensure continuous and accurate debris surveillance. This cluster is positioned relatively isolated from other clusters, indicating that these optical monitoring technologies are specialized and focused specifically on tracking and observation, distinct from more ADR or mitigation technologies. The separation also reflects the unique role that monitoring systems play in the broader context of space debris management, as they provide the necessary data for real-time tracking and long-term debris management strategies.

Cluster 2 (Green): Capture and Removal of Space Debris Using Flexible Systems: located near the lower-left area of the visualization, focuses on Capture and Removal of Space Debris Using Flexible Systems. This cluster includes patents that describe flexible and deployable systems, such as nets and harpoons, designed to capture and remove debris from orbit. The patents address the challenge of safely capturing debris with minimal risk of collision. The relevance of this cluster lies in its focus on innovative methods for physically interacting with space debris, providing practical solutions for actively removing debris from space. Positioned somewhat independently from other clusters, it reflects the unique nature of these capture systems compared to other debris mitigation or monitoring technologies. The cluster's isolated position in the visualization may also indicate a specialized technological focus distinct from more conventional removal approaches.

Cluster 3 (Blue): Fluid Propulsion and Discharge Systems for Spacecraft End-of-Life and Debris Deviation: located centrally in the visualization, focuses on Fluid Propulsion and Discharge Systems for Spacecraft End-of-Life and Debris Deviation. The patents in this cluster address the safe management of space debris and the passivation of spacecraft at the end of their operational lifetimes. Specifically, one patent involves the use of gas clouds to deviate the trajectory of space debris, while another details a fluid passivation procedure for satellites, preventing future debris generation. The position of this cluster in the visualization highlights its relevance to both removal and prevention policies, connecting the safe deorbiting of space debris with proactive measures for managing satellite end-of-life. Its central location suggests it plays a key role in bridging ADR techniques and long-term strategies for debris prevention.

Cluster 4 (Yellow): Debris Detection and Monitoring Using Microsatellites: located at the top-right of the visualization and consisting of a single node, represents a highly specialized technology focused on Debris Detection and Monitoring Using Microsatellites. This cluster is centred around a single patent that describes a microsatellite equipped with imaging systems designed to detect and track space debris. The system processes images to determine debris characteristics such as size, speed, and trajectory, contributing to space debris monitoring and mitigation efforts. The isolation of this cluster from the rest of the visualization highlights its unique focus on satellite-based debris detection, distinguishing it from other clusters that may deal with more generalized or integrated debris removal and mitigation systems. The independent position in the visualization reflects the specialized and singular nature of this technology within the broader scope of space debris management.

Cluster 5 (Purple): Passive Optical Detection of Space Debris: located in the lower left corner of the visualization and consisting of a single node, focuses on Passive Optical Detection of Space Debris. The system described in this cluster uses CCD cameras and triangulation methods to detect and monitor space debris from a satellite platform. The isolated position of this cluster in the visualization highlights its specialized nature, focusing on passive detection techniques that operate without active radar or laser systems. This distinction may explain its separation from other clusters, as it relies on low-power, optical-based observation methods that differ from more ADR or monitoring systems found elsewhere. Its relevance lies in providing a lightweight and efficient solution for tracking space debris with minimal energy consumption, which is crucial for long-term, sustainable monitoring efforts in space.

Cluster 6 (Cyan): Laser-Based Space Debris Removal System: located near the lower part of the visualization, focuses on Laser-Based Space Debris Removal Systems. This patent describes a system that uses laser technology to vaporize the material composing space debris, altering its orbit and effectively removing it from harmful paths. The position of this cluster, somewhat separated from other nodes, highlights its distinct and specialized approach to space debris removal. The use of lasers is a unique method compared to other mechanical or electromagnetic systems seen in other clusters, and this isolation in the visualization reflects its cutting-edge and specific role in space debris management. This cluster's relevance lies in providing an innovative solution for removing space debris without physical contact, utilizing energy-based interventions to mitigate debris threats.

5.3.8 UK

Figure 33: Visualisation of UK Display Key Debris Patents Clusters

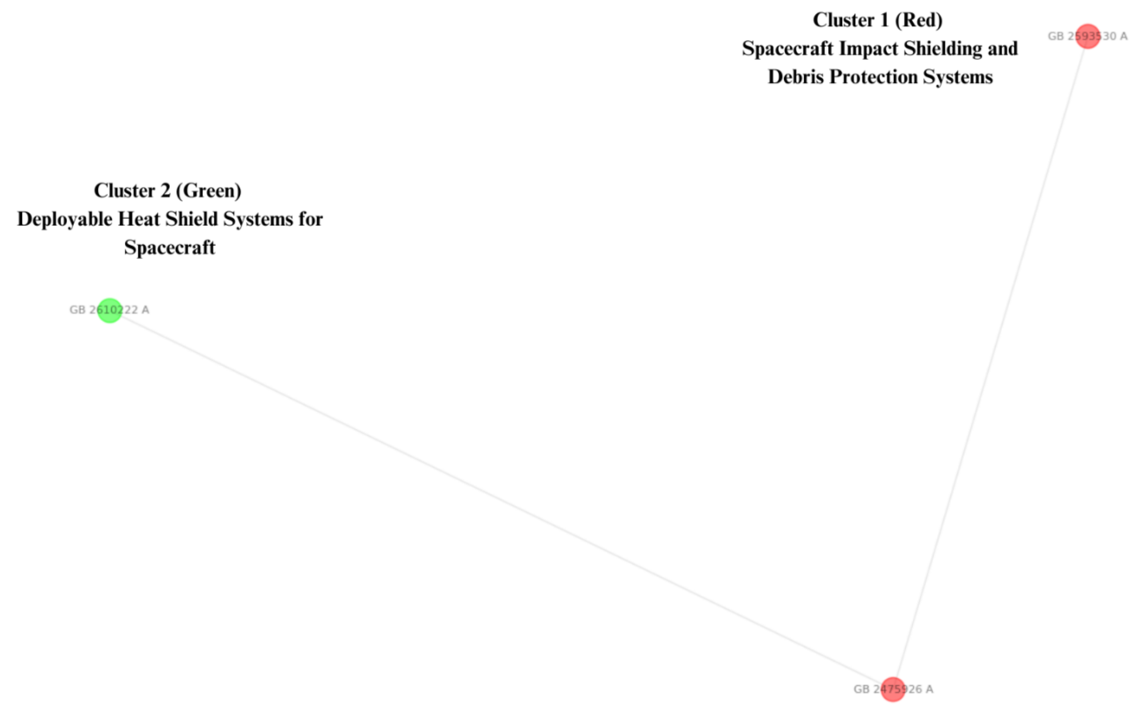


Figure 33 represents the results of the DBSCAN clustering algorithm visualization for all countries.

Cluster 1 (Red): Spacecraft Impact Shielding and Debris Protection Systems: focuses on Spacecraft Impact Shielding and Debris Protection Systems. This cluster contains two patents addressing mitigation policies, highlighting solutions that enhance spacecraft protection from space debris impacts. Both patents introduce innovative materials like graphene foam and ceramic powder, alongside deployable shields that increase atmospheric drag to aid deorbiting. The isolated placement of this cluster in the visualization suggests that the shielding technologies developed here are specialized and distinct from other space debris removal or monitoring technologies. This cluster's relevance lies in its contribution to reducing the damage caused by space debris through protective and stowable shielding systems, which are essential for maintaining spacecraft integrity in debris-filled orbits.

Cluster 2 (Green): Deployable Heat Shield Systems for Spacecraft: focuses on Deployable Heat Shield Systems for Spacecraft, with a single patent. This patent describes a heat shield that deploys in an origami-like pattern, designed to protect spacecraft during atmospheric re-entry and against space debris impacts. The isolated position of this cluster highlights its unique role in providing both thermal protection and debris mitigation. Its relevance lies in its dual-functionality, contributing to mitigation policies by protecting spacecraft from extreme heat and potential debris damage during critical mission phases, such as re-entry or in debris-heavy environments. This innovative approach is crucial for enhancing spacecraft durability and ensuring mission safety in high-risk scenarios.

5.3.9 Germany

Figure 34: Visualisation of Germany Display Key Debris Patents Clusters

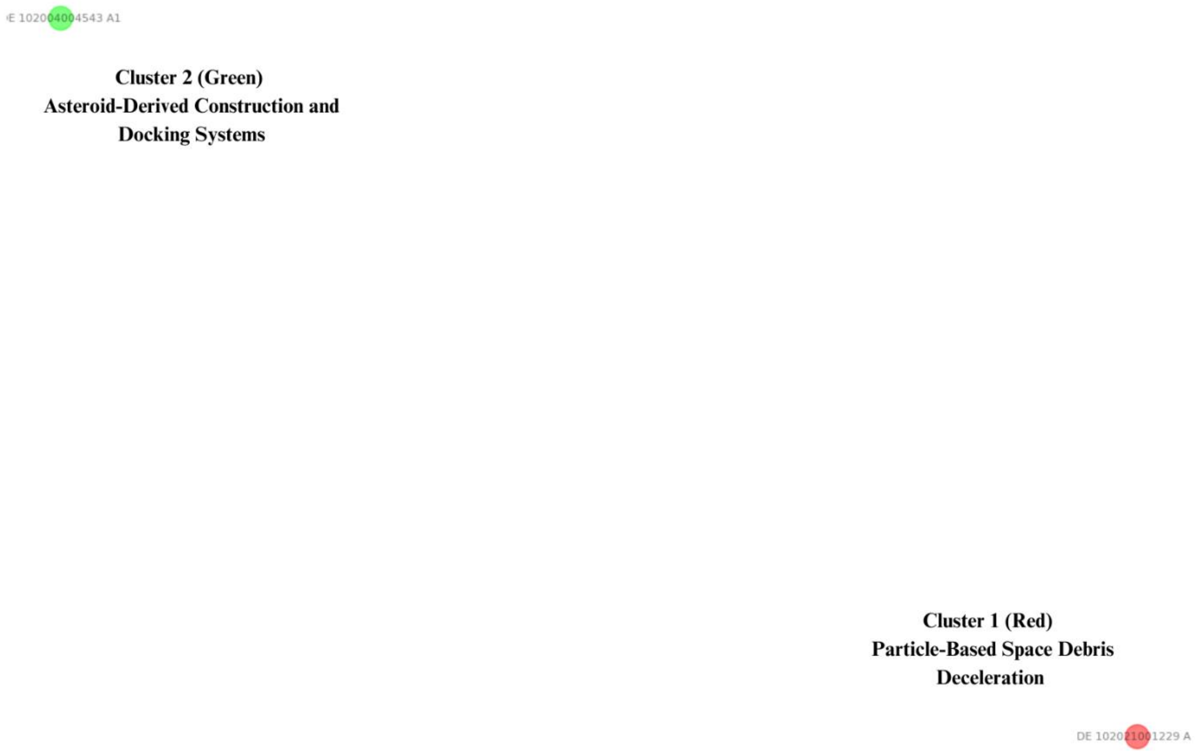


Figure 34 represents the results of the DBSCAN clustering algorithm visualization for all countries.

Cluster 1 (Red): Particle-Based Space Debris Deceleration: focuses on Particle-Based Space Debris Deceleration. This patent outlines a method for slowing down space debris using particles that collide with debris without destroying it, making it easier to manage or remove. Its isolated position in the visualization emphasizes its specialized approach, distinct from other debris removal technologies. The relevance of this cluster lies in its focus on removal policies, specifically addressing the challenge of decelerating debris rather than destroying it, which prevents the generation of further small fragments and orbital clutter, enhancing space safety.

Cluster 2 (Green): Asteroid-Derived Construction and Docking Systems: focuses on Asteroid-Derived Construction and Docking Systems. The patent describes using asteroid materials to construct docking stations or large space infrastructure, indirectly addressing space debris disposal. The space tugs equipped with nets collect asteroids, which are then used for construction, promoting sustainable space infrastructure development without generating more debris. This cluster's isolated position suggests its unique approach in combining construction with asteroid-derived materials and space debris management, offering an innovative way to mitigate the challenges of long-term space habitation.

6 Discussion: technological and policy solutions for a sustainable orbital environment

A sustainable space environment is a concept that has multiple interpretations depending on the context, ranging from economic sustainability of space ventures to environmental sustainability of the orbital space environment (Newman and Williamson, 2018). In this paper, as mentioned earlier, we adopt the definition provided by the UN COPUOS, (2018), which describes space sustainability as the ability to conduct space activities indefinitely while ensuring equitable access to outer space for future generations. A sustainable space environment means maintaining Earth's orbital regions in a condition that allows the continuous use of space-based technology for communication, exploration, and scientific research without jeopardising future missions. This requires a focus on addressing the increasing congestion in our orbits and the threat of space debris.

One of the major challenges in achieving a sustainable orbital environment is the lack of standardised methods for ADR (Hakima and Emami, 2018). Programs like RemoveDEBRIS, led by the University of Surrey, aim to demonstrate ADR technologies such as nets and harpoons for capturing and removing debris from orbit (Forshaw et al., 2016). This program seeks to address the problem of approximately 40,000 pieces of space debris currently orbiting Earth. Similarly, Astroscale's COSMIC mission, scheduled for launch in 2025, aims to provide a commercial debris removal service by safely capturing and deorbiting debris (Astroscale, 2024). The ClearSpace1 mission, led by the European Space Agency (ESA), employs a robotic system with multiple arms to capture debris, demonstrating the viability of ADR with the intent of deorbiting larger objects in the future (Clearspace, 2023) ESA's CleanSpace initiative, which explores debris capture technologies through advanced robotics and imaging systems, and the eDeorbit mission, which aims to remove a large ESA-owned object, represent further efforts to address debris removal on an institutional level (ESA, 2018).

Despite these advancements, technology remains a limiting factor in combating space debris. According to Ribeiro et al (2018) there are three primary strategies to combating space debris: prevention, mitigation, and removal. Prevention strategies aim to reduce space debris by implementing measures like satellite passivation, which depletes energy reserves to prevent explosions. Post-mission disposal strategies include programming satellites in LEO to re-enter Earth's atmosphere within 25 years, while those in geostationary orbit (GEO) are moved to a "graveyard orbit" to avoid collisions (Ribeiro et al., 2018).

Mitigation strategies involves both monitoring space debris and utilizing technologies that reduce the impact of collisions on spacecraft. Monitoring technologies, such as NASA’s CCD Debris Telescope and radar systems used by various space agencies, track and catalogue debris in real-time, allowing for collision avoidance manoeuvres. Additionally, supporting technologies, like impact-resistant bumpers or gas leak prevention systems, enhance spacecraft resilience. These technologies don't remove debris but help mitigate the risks and consequences of debris impacts. For example, a ceramic impact-resistant bumper can crush incoming debris, protecting the spacecraft from damage (Ribeiro et al., 2018).

Finally, removal strategies, or ADR is a more direct method aimed at physically capturing and eliminating debris. Several innovative methods are being developed, including robotic arms, nets, and harpoons. These technologies target large, non-cooperative debris in LEO, which poses the greatest threat due to the high density of objects. However, no debris removal method has been fully deployed yet, as these technologies are still in experimental stages (Ribeiro et al., 2018).

The aforementioned space debris programs demonstrate that while significant progress has been made in developing various debris management technologies, the current focus remains on refining and testing solutions across these key strategies. Our clustering analysis categorises each space debris-related patents into one of the three primary strategies: prevention, mitigation, and removal.

Figure 35: Countries and Regions focusing on Removal Technologies

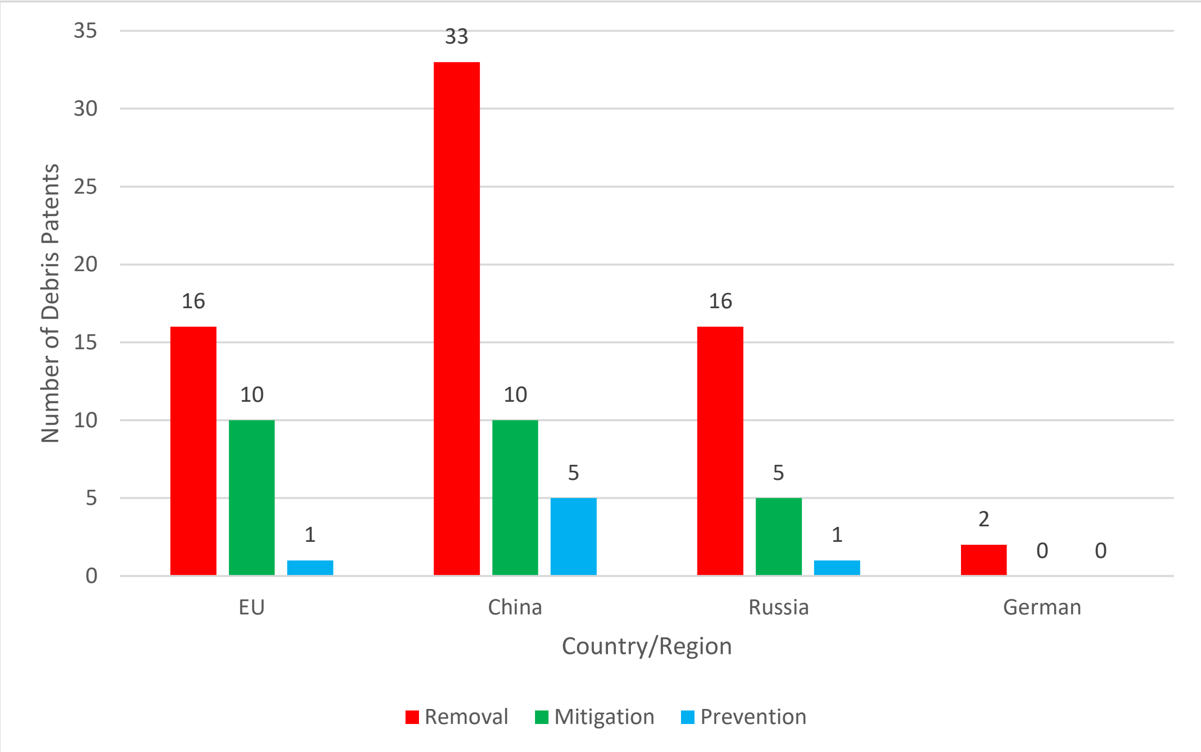


Figure 35 presents the countries/regions that focus on removal technologies from the cluster visualisations in section 5.3.

The results indicate that the European Union (EU), China, Russia, and Germany primarily focus on debris removal technologies, which supports the global push toward ADR as a key strategy. For instance, the EU's patents reveal a strong emphasis on space traffic management, debris detection, and debris elimination systems (e.g., Cluster 1: Space Traffic Management and Debris Intrusion Warning Systems and Cluster 2: Harpoon and Tether-Based Debris Removal Systems). These clusters highlight the EU's concerted effort to advance debris removal through a variety of technological innovations, including hypervelocity shielding and harpoon-based collection systems. China's clusters focus on removal and capture technologies (e.g., Cluster 1: Space Debris Removal and Capture Technologies) as well as active debris management systems that demonstrate the country's intent to tackle space debris head-on. Russia's focus on magnetic and mechanical systems for debris removal (e.g., Cluster 1: Magnetic and Mechanical Systems for Space Debris Collection and Removal) and Germany's patent work on deceleration of space debris using particle-based systems reinforce the significance of debris removal in global space sustainability strategies. These technological advances highlight the increasing recognition that ADR is a critical aspect of managing orbital debris.

Figure 36: Countries and Regions focusing on Mitigation Technologies

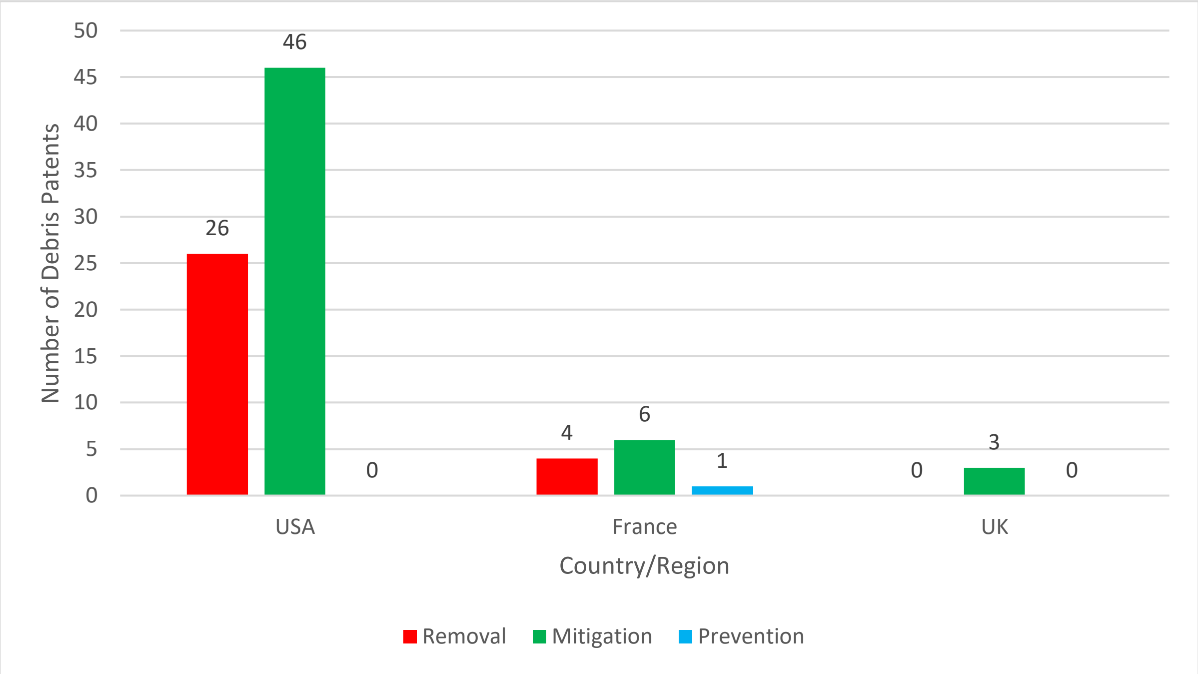


Figure 36 presents the countries/regions that focus on mitigation technologies from the cluster visualisations in section 5.3.

On the other hand, the USA, France, and the UK prioritise mitigation strategies. The USA focuses on spacecraft protection, debris detection, and tracking technologies, with Cluster 1 highlighting Spacecraft Protection and Debris Mitigation Systems and Cluster 2 focusing on Debris Detection, Tracking, and Modelling Systems. This focus on mitigation technologies may reflect the USA's immediate need to protect valuable space assets from debris impacts rather than removing debris outright. Similarly, France emphasises optical monitoring and detection systems (e.g., Cluster 1: Optical Monitoring Systems for Space Debris Surveillance) and laser-based debris removal, which aligns with the country's focus on developing precise and real-time debris management solutions. The UK's focus on spacecraft shielding and protection systems (e.g., Cluster 1: Spacecraft Impact Shielding and Debris Protection Systems) reinforces the importance of safeguarding operational satellites against debris impacts.

Figure 37: Japen Debris Management Technological Focus

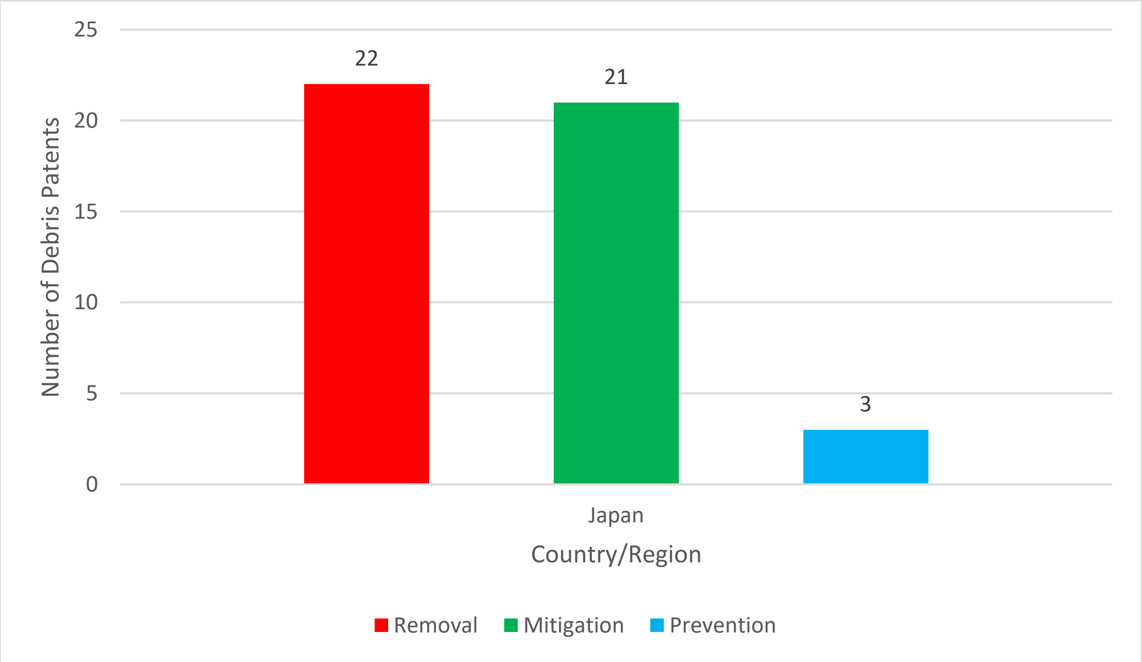


Figure 37 presents Japan’s debris management technological focus from the cluster visualisations in section 5.3.

Japan stands out as the only country from the dataset balancing its focus between mitigation and removal strategies. With 21 patents focused on mitigation and 22 on removal, Japan is uniquely positioned, developing technologies for both shielding spacecraft from debris (e.g., Cluster 1: Space Debris Shielding, Removal, and Protection Technologies) and removing debris from orbit (e.g., Cluster 2: Space Debris Removal and Satellite Deployment Technologies). This balanced approach is significant because it reflects Japan's strategy to address both immediate and long-term sustainability challenges in space, with an emphasis on both damage prevention and debris reduction.

Figure 38: All Countries Combined Debris Management Technological Focus

Figure 38 showcases the totalling each debris management technology focus based on the clusters in section 5.3. It should be noted that this chart does not include the data from all country visualisation (Section 5.3.1).

When analysing all the patents (231) involved in our clustering visualization, it becomes clear that mitigation and removal strategies are nearly equal in focus, with 101 patents pertaining to mitigation and 119 patents related to removal. This relatively even distribution of patents highlights the joint global drive for innovation in both strategies, acknowledging the need to monitor, detect and track debris while also addressing the long-term buildup of debris through ADR. The balance between mitigation and removal efforts indicates that the space industry recognizes that sustainable space operations require both immediate protection solutions and proactive debris reduction strategies, ensuring the orbital environment remains usable for future generations.

One of the outcomes of our analysis is the relatively low number of patents focused on prevention strategies for space debris, with only 11 out of 231 patents addressing this strategy. This raises questions about the underlying reasons for the lack of emphasis on prevention compared to mitigation and removal strategies. Several factors may contribute to this difference and understanding them is key to contextualizing the future of space sustainability efforts.

First, the growing accumulation of space debris, particularly in LEO, presents an urgent and immediate threat to operational satellites, space stations, and future missions. Given the high density of debris in LEO and the risk of a Kessler event, the likelihood of collisions is elevated, making mitigation and removal strategies a priority. ADR technologies such as robotic arms, harpoons, and capture nets are vital solutions to this problem and consequently have received significant attention and innovation efforts (Ribeiro et al., 2018). This urgency may explain the greater number of patents focused on real-time debris monitoring and removal methods, which address the already critical space debris problem.

Another key reason for the lack of patent focus on prevention strategies is that prevention technologies may already be technologically mature and widely standardized. For instance, satellite passivation and post-mission disposal measures, such as deorbiting satellites within 25 years or moving them to graveyard orbits, are well-established practices. These technologies are regulated by international guidelines and do not require the same level of novel innovation as removal and monitoring technologies, which are still experimental or developmental in many cases (Forshaw et al., 2019). With the increasing threat of a Kessler event, there may have been a stronger push toward advanced mitigation and removal strategies. This push is crucial to ensure the long-term sustainability of space activities, but as frameworks and regulations evolve, it is likely that more attention will return to innovative prevention technologies designed to reduce future debris accumulation.

While prevention strategies like satellite passivation are supported by international guidelines, advanced debris removal technologies face regulatory challenges. As mentioned in section 3, outdated legal frameworks, like the 1967 OST and 1972 Liability Convention, hinder the deployment of emerging ADR technologies, creating a growing gap between advancements and regulations.

For example, the OST treats debris as the property of the launching state, even if non-functional, creating legal ambiguities that make removing foreign debris without authorization legally complex. Article VIII of the OST states that ownership of space objects, including debris, remains with the launching country, requiring state-level approval for removal (UNOOSA, 1967). This creates significant bureaucratic hurdles, slowing ADR efforts and discouraging private investments.

Discussions are underway within international bodies to update legal frameworks for space debris management. Proposals include agreements to allow debris removal regardless of ownership, provided certain protocols are followed (Froehlich, 2019). Until such frameworks are established, legal challenges will continue to limit the effectiveness of current debris removal technologies.

Addressing these regulatory challenges is crucial not only for enabling the removal of space debris but also for incentivizing technological innovation in debris management. By creating clear legal frameworks and assigning responsibilities, international agreements can unlock new economic incentives that drive both public and private investments in space debris removal and mitigation technologies.

Our research and examples from innovative space debris programs, such as ClearSpace-1, showcase potential technological innovation to combat the space debris management agenda. However, the full realization of these innovations may be delayed if policy frameworks are not aligned with the emerging technologies. One effective way to accelerate the development and deployment of these technologies is by introducing economic incentives through policy. Economic incentives can provide businesses and governments with the motivation to invest in debris management solutions, fostering a sustainable orbital environment and ensuring long-term space utilization (Zaloznova and Chekina, 2023).

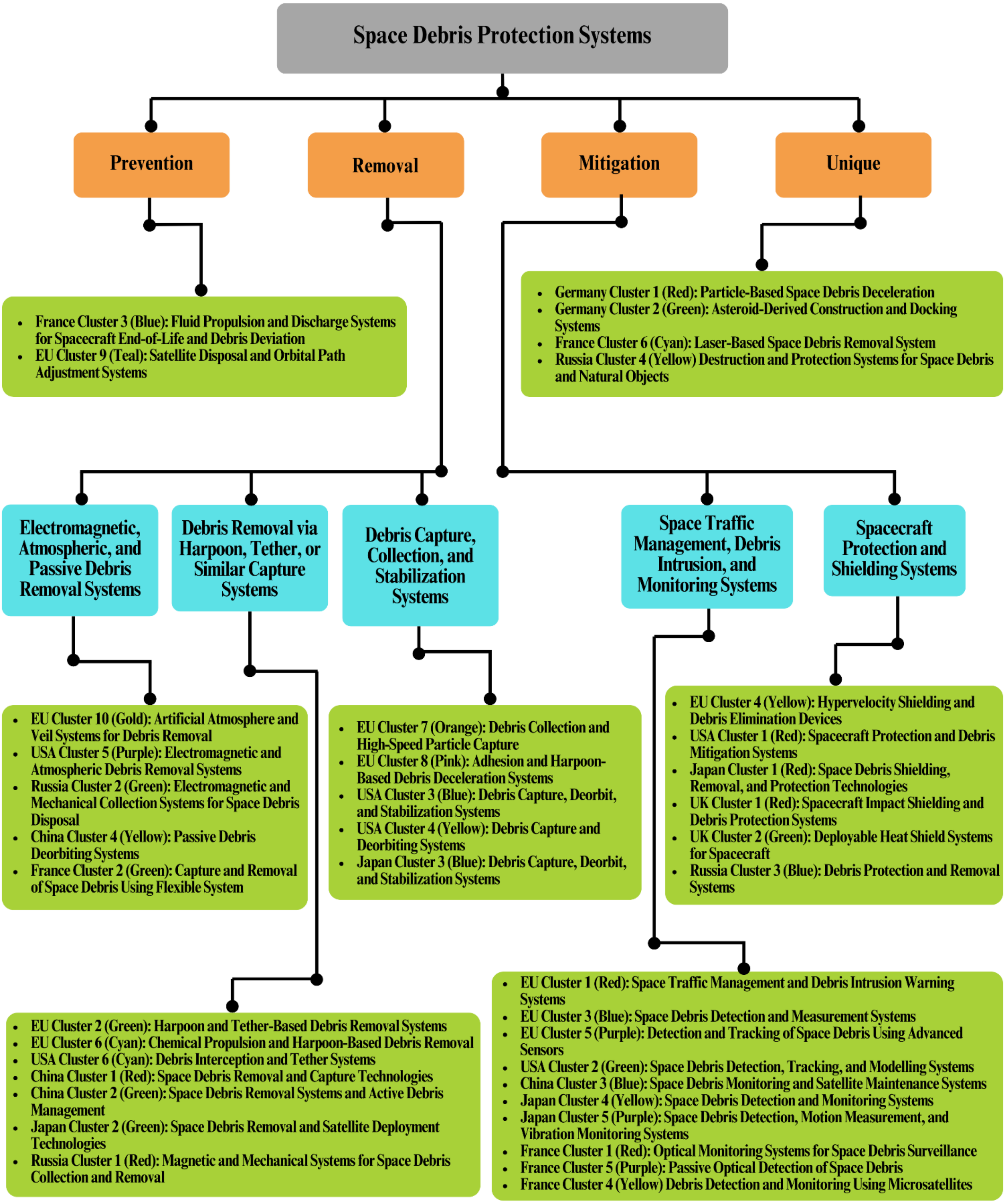
Future research can explore the implementation of space-related policy related economic incentives to drive innovation. An example of this could be a space tax based on the prevention technologies present on an entity's payloads. This tax could reward organizations that invest in advanced debris prevention technologies, such as passivation systems or post-mission disposal strategies, by offering tax reductions or exemptions. Conversely, entities that do not include such technologies in their payloads would face higher taxes, incentivizing them to adopt more sustainable practices. Further research is needed to determine where the revenue from such taxes would be allocated, whether towards space sustainability funds, research and development grants, or international cooperative efforts.

Added to this future research can explore the idea of orbital bans imposed on entities that generate excessive amounts of space debris. Such bans would limit their access to critical orbits, such as LEO, forcing them to either invest in R&D to develop more effective debris removal, mitigation and prevention technologies or to purchase these technologies from companies that have made those investments. This could foster an open market for space debris solutions, encouraging the growth of businesses focused on sustainability. Entities would have strong economic motivation to comply with debris regulations or risk losing access to lucrative orbital real estate.

For economic incentives such as space taxes and orbital bans to be effective, they must be supported by international policy frameworks that facilitate space sustainability. Policies must ensure that the economic benefits of developing and deploying debris management technologies are clear and accessible to spacefaring entities. Furthermore, policies that provide funding opportunities, tax credits, or research grants for companies developing space debris removal and mitigation technologies would help encourage continued innovation. For example, programs such as ClearSpace-1, which utilizes robotic arms to capture debris, and COSMIC, which focuses on ADR, could serve as models for incentivized R&D efforts.

Moreover, policies could be designed to reward entities that share their debris management innovations with the international community, further accelerating the development of a global space sustainability network. As seen in our research, spacefaring nations are focusing on removal and mitigation strategies, and the development of prevention technologies could be accelerated with proper policy and financial incentives.

Figure 39: Flow Chart of Space Debris Protection Systems



This figure shows a flow chart of all the clusters from the patent ID DBSCAN analysis from section 5.3.

Aside from exploring policies future researchers can explore the technical aspects of the debris agenda as well. Figure 39 shows all the clusters, 39, that were part of the cluster visualisation in different technological domains. The information provided in the clusters offers a valuable foundation for future research aimed at writing technical papers and exploring the potential effectiveness of space debris removal, mitigation, and prevention strategies. Each cluster highlights emerging innovative technologies in space debris management from different space-faring nations, providing a comprehensive view of how countries are approaching the issue. Future research can leverage this data to analyse the comparative effectiveness of various strategies, such as harpoon-based removal systems, electromagnetic and atmospheric solutions, and spacecraft protection technologies.

By focusing on these clusters, researchers can delve deeper into the technological innovations each country is developing. For instance, comparing the different technologies for space debris monitoring systems from the USA[7], EU[8], China[9] and Japan[10] could offer insights into the technological strengths and limitations of each approach. Similarly, the unique laser-based removal systems from France and particle-based deceleration systems from Germany provide new avenues for exploring cutting-edge debris removal solutions. Future technical papers could also assess the cost-effectiveness, scalability, and operational feasibility of these technologies, helping guide policy and investment decisions in space debris management.

This detailed clustering of technologies also allows researchers to track regional innovation trends and identify technology gaps, thus fostering collaboration or competition between nations in addressing the global challenge of space debris. Such analyses could further be supported by case studies of existing programs, like ClearSpace-1 or Astroscale, helping to forecast the long-term impact of specific technologies on space sustainability.

Our research results, including the figures showcasing the main space debris technology strategies, provide a foundation for future exploration of technical, economic and policy frameworks that can support sustainable space activities. By aligning economic incentives with regulatory policies, governments and private organizations can help ensure that space remains accessible and safe for future generations. Further research can build on these findings to explore how different debris management strategies (prevention, mitigation, and removal) compare in terms of effectiveness and cost-efficiency, with an emphasis on their global impact.

As we look to the future, it is clear that economic incentives, supported by comprehensive regulatory frameworks, can play a crucial role in driving the next wave of innovation in space debris

[7] USA Cluster 2 (Green): Space Debris Detection, Tracking, and Modelling Systems

[8] EU Cluster 3 (Blue): Space Debris Detection and Measurement Systems

[9] China Cluster 3 (Blue): Space Debris Monitoring and Satellite Maintenance Systems

[10] Japan Cluster 5 (Purple) Space Debris Detection, Motion Measurement, and Vibration Monitoring Systems

management. This, in turn, will ensure the sustainability of orbital environments, balancing technological advancements with policy-driven economic benefits.

6.1 Limitations

As with any piece of research, limitations are expected. One notable limitation of this study is the reliance on a custom DBSCAN clustering algorithm, created in Python for this analysis. While DBSCAN is widely recognized for its effectiveness in density-based clustering, the custom nature of our implementation opens it to potential scrutiny. Experts in data grouping and clustering algorithms might argue against its robustness, as the custom adjustments may not align with best practices in some contexts. Added to this, the 756-dimensional display key data posed a challenge for DBSCAN, as high-dimensionality can lead to redundant distance calculations, impacting clustering accuracy (Chen et al., 2021). To address this, we applied PCA, reducing the data to 7 components while retaining 90% of the variance. This improved accuracy but highlights potential limitations in generalising our results due to the data structure.

Another limitation was the method used to capture space-related patents. Despite these efforts, there remains the possibility that not all space-related patents were captured. Some relevant patents may have been excluded due to variations in classification or keyword use, which may have influenced the final dataset and thus the results of the analysis.

Moreover, our research focused primarily on the main spacefaring nations, represented by countries with the largest government spending on space exploration and development. This approach left out nations that could have contributed to the global space debris landscape, limiting the diversity of technological insights. Evaluating more countries, particularly those with developing space industries, may have uncovered additional technological clusters that were not identified in our current analysis. Future research could extend this work by focusing on these countries as well as specific entities or private companies using applicant and inventor information from patent data, which would provide a more granular view of innovation patterns in space debris management. This gap indicates the potential for broader and more inclusive studies that might reveal novel technologies or approaches that have been developed outside of the primary spacefaring nations included in this study.

7 Conclusions

The accelerating commercialisation of outer space, alongside the growing threat of space debris, underscores the urgency of developing robust and sustainable debris management strategies. Our analysis has showcased some upcoming technologies to tackle the critical need for technological innovations in debris prevention, mitigation, and removal, alongside more supportive regulatory frameworks to ensure the long-term usability of Earth's orbital environments. The clustering analysis of space debris patents reveals a concentrated focus on mitigation and removal strategies across major space-faring nations. However, the underrepresentation of patents related to prevention technologies highlights a significant gap in the current innovation landscape.

Our study also points to the critical role that international cooperation and updated legal frameworks must play in addressing these challenges. Existing treaties, such as the Outer Space Treaty, fall short of offering the enforceable guidelines needed to manage space debris effectively. As space debris remains a transboundary issue, global governance mechanisms are essential to ensure that all stakeholders, including private companies and national governments, are held accountable for their contributions to space sustainability (Martin-Lawson et al., 2024). Without a cohesive and legally binding framework, even the most advanced debris removal technologies may struggle to find practical application.

In conclusion, while technological advancements offer promising solutions for space debris management, the real challenge lies in aligning these innovations with supportive policy frameworks. The introduction of economic incentives through policies, such as taxes or orbital restrictions, could further drive the development and adoption of debris prevention and removal technologies. Our research employs future researchers to explore the potential economic, legal, and technological mechanisms that can ensure a sustainable and safe orbital environment for future generations.

8 Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

9 Data availability

Data will be made available on request.

10 References

Abashidze, A., Chernykh, I. and Mednikova, M. (2022) Satellite constellations: International legal and technical aspects. *Acta Astronautica*, 196: 176–185. doi:10.1016/j.actaastro.2022.04.019.

Achlioptas, D. (2003) Database-friendly random projections: Johnson-Lindenstrauss with binary coins. *Journal of Computer and System Sciences*, 66 (4): 671–687. doi:10.1016/S0022-0000(03)00025-4.

Actkinson, B. and Griffin, R.J. (2023) Detecting plumes in mobile air quality monitoring time series with density-based spatial clustering of applications with noise. *Atmospheric Measurement Techniques*, 16 (14): 3547–3559. doi:10.5194/AMT-16-3547-2023.

Agapito, G., Milano, M. and Cannataro, M. (2022) A Python Clustering Analysis Protocol of Genes Expression Data Sets. *Genes 2022, Vol. 13, Page 1839*, 13 (10): 1839. doi:10.3390/GENES13101839.

Aliwy, Dr.A.H. and Aljanabi, Dr.K.B.S. (2016) An Efficient Algorithm for Initializing Centroids in K-means Clustering. *Journal of Kufa for Mathematics and Computer*, 3 (2): 18–24. doi:10.31642/JOKMC/2018/030203.

Allen, J., Arion, L., Barentine, D., et al. (2019) Light Pollution, Radio Interference, and Space Debris: Threats and Opportunities in the 2020s. *Bulletin of the AAS*, (7): 51. Available at: https://scholarworks.smith.edu/ast_facpubs/57/ (Accessed: 10 June 2022).

Altuntas, S., Erdogan, Z. and Dereli, T. (2020) A clustering-based approach for the evaluation of candidate emerging technologies. *Scientometrics*, 124 (2): 1157–1177. doi:10.1007/S11192-020-03535-0.

Arendt, C., Patchou, M., Bocker, S., et al. (2021) Pushing the Limits: Resilience Testing for Mission-Critical Machine-Type Communication. *2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall)*, 2021-September: 01–06. doi:10.1109/VTC2021-FALL52928.2021.9625209.

Astroscale (2024) *Astroscale's UK National ADR Mission COSMIC Achieves Significant Progress in Space Cleanup Efforts*. Available at: https://astroscale.com/astroscales-uk-national-adr-mission-cosmic-achieves-significant-progress-in-space-cleanup-efforts/ (Accessed: 8 September 2024).

Balka, K.R. and De Nardo, D. (2021) Molecular and spatial mechanisms governing STING signalling. *The FEBS Journal*, 288 (19): 5504–5529. doi:10.1111/FEBS.15640.

Barash, E.H. (1996) Experimental Uses, Patents, and Scientific Progress. *Northwestern University Law Review*, 91. Available at: https://heinonline.org/HOL/Page?handle=hein.journals/illlr91&id=687&div=&collection= (Accessed: 31 August 2024).

Baruffaldi, S.H. and Simeth, M. (2015) Patent disclosure and the diffusion of knowledge. *Academy of Management Proceedings*, 2015 (1): 18170. doi:10.5465/AMBPP.2015.18170ABSTRACT.

Bastida Virgili, B., Dolado, J.C., Lewis, H.G., et al. (2016) Risk to space sustainability from large constellations of satellites. *Acta Astronautica*, 126: 154–162. doi:10.1016/j.actaastro.2016.03.034.

Bastien, D. and Somanah, R. (2019) An Unsupervised Machine Learning Analysis of the FIRST Radio Sources. *Advances in Intelligent Systems and Computing*, 863: 33–41. doi:10.1007/978-981-13-3338-5_4.

Belz, A. and Giga, A. (2018) Of Mice or Men: Management of Federally Funded Innovation Portfolios With Real Options Analysis. *IEEE Engineering Management Review*, 46 (3): 75–86. doi:10.1109/EMR.2018.2847313.

Benabdellah, A.C., Benghabrit, A. and Bouhaddou, I. (2019) A survey of clustering algorithms for an industrial context. *Procedia Computer Science*, 148: 291–302. doi:10.1016/J.PROCS.2019.01.022.

Benson, C.L. and Magee, C.L. (2015) Quantitative Determination of Technological Improvement from Patent Data. *PLoS ONE*, 10 (4). doi:10.1371/JOURNAL.PONE.0121635.

Biermann, F., Pattberg, P., van Asselt, H., et al. (2009) The Fragmentation of Global Governance Architectures: A Framework for Analysis. *Global Environmental Politics*, 9 (4): 14–40. doi:10.1162/GLEP.2009.9.4.14.

Boly, M., Perlbarg, V., Marrelec, G., et al. (2012) Hierarchical clustering of brain activity during human nonrapid eye movement sleep. *Proceedings of the National Academy of Sciences of the United States of America*, 109 (15): 5856–5861. doi:10.1073/PNAS.1111133109.

Bombardelli, C. and Peláez, J. (2012) Ion Beam Shepherd for Contactless Space Debris Removal. *https://doi.org/10.2514/1.51832*, 34 (3): 916–920. doi:10.2514/1.51832.

Bongers, A. and Torres, J.L. (2023) Orbital debris and the market for satellites. *Ecological Economics*, 209: 107831. doi:10.1016/j.ecolecon.2023.107831.

Bonnal, C., Ruault, J.-M. and Desjean, M.-C. (2013) Active debris removal: Recent progress and current trends. *Acta Astronautica*, 85: 51–60. doi:10.1016/j.actaastro.2012.11.009.

Buja, A., Swayne, D.F., Littman, M.L., et al. (2008) Data Visualization With Multidimensional Scaling. *Journal of Computational and Graphical Statistics*, 17 (2): 444–472. doi:10.1198/106186008X318440.

Chakraborty, M., Byshkin, M. and Crestani, F. (2020) Patent citation network analysis: A perspective from descriptive statistics and ERGMs. *PLoS ONE*, 15 (12 December). doi:10.1371/JOURNAL.PONE.0241797.

Chen, Y., Zhou, L., Bouguila, N., et al. (2021) BLOCK-DBSCAN: Fast clustering for large scale data. *Pattern Recognition*, 109: 107624. doi:10.1016/J.PATCOG.2020.107624.

Clearspace (2023) *A mission to make space sustainable*. Available at: https://clearspace.today/ (Accessed: 22 May 2023).

Cohen, E. and Spector, S. (2020) Space tourism-past to future : a perspective article. *Tourism Review*, 75 (1): 136–139. doi:10.1108/TR-03-2019-0083/FULL/XML.

Crane, K.W., Linck, E., Lal, B., et al. (2020) *Projections of the Future Size of the Space Economy*. Estimating the Value of Economic Activities in and for Space. Institute for Defense Analyses. Available at: http://www.jstor.org/stable/resrep25331.7.

Dennerley, J.A. (2018) State Liability for Space Object Collisions: The Proper Interpretation of ‘Fault’ for the Purposes of International Space Law. *European Journal of International Law*, 29 (1): 281–301. doi:10.1093/EJIL/CHY003.

Drmola, J. and Hubik, T. (2018) Kessler Syndrome: System Dynamics Model. *Space Policy*, 44–45: 29–39. doi:10.1016/J.SPACEPOL.2018.03.003.

Dugan, H.A., Bartlett, S.L., Burke, S.M., et al. (2017) Salting our freshwater lakes. *Proceedings of the National Academy of Sciences of the United States of America*, 114 (17): 4453–4458. doi:10.1073/PNAS.1620211114.

ESA (2018) *ESA's e.Deorbit debris removal mission reborn as servicing vehicle*. Available at: https://www.esa.int/Space_Safety/Clean_Space/ESA_s_e.Deorbit_debris_removal_mission_reborn_as_servicing_vehicle (Accessed: 8 September 2024).

Eshetu, A., Teshome, G. and Abebe, T. (2020) Learning Word and Sub-word Vectors for Amharic (Less Resourced Language). *International Journal of Advanced Engineering Research and Science*, 7 (8): 358–366. doi:10.22161/IJAERS.78.39.

Ester, M., Kriegel, H.-P., Sander, J., et al. (1996) A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise. *kddm*, pp. 226–331. Available at: https://ui.adsabs.harvard.edu/abs/1996kddm.conf..226E/abstract (Accessed: 27 August 2024).

Evans, K., Love, T. and Thurston, S.W. (2015) Outlier Identification in Model-Based Cluster Analysis. *Journal of Classification*, 32 (1): 63–84. doi:10.1007/S00357-015-9171-5.

Fahim, A. (2022) An Extended DBSCAN Clustering Algorithm. *International Journal of Advanced Computer Science and Applications*, 13 (3): 245–258. doi:10.14569/IJACSA.2022.0130331.

Fahim, A.M., Saake, G., M. Salem, A.-B., et al. (2008) K-Means for Spherical Clusters with Large Variance in Sizes. *International Journal of Computer, Electrical, Automation, Control and Information Engineering*, 2: 2923–2928.

Forshaw, J.L., Aglietti, G.S., Navarathinam, N., et al. (2016) RemoveDEBRIS: An in-orbit active debris removal demonstration mission. *Acta Astronautica*, 127: 448–463. doi:10.1016/j.actaastro.2016.06.018.

Fortunato, S. (2010) Community detection in graphs. *Physics Reports*, 486 (3–5): 75–174. doi:10.1016/J.PHYSREP.2009.11.002.

Fraley, C. and Raftery, A.E. (1999) MCLUST: Software for Model-Based Cluster Analysis. *Journal of Classification*, 16 (2): 297–306. doi:10.1007/S003579900058.

Fraley, C. and Raftery, A.E. (2002) *MCLUST: Software for Model-Based Clustering, Density Estimation and Discriminant Analysis*. doi:10.21236/ADA459792.

Freeland, S. (2020) The limits of law: challenges to the global governance of space activities. *Journal and proceedings of the Royal Society of New South Wales*, 153 (1): 70–82. doi:10.5962/P.361903.

Froehlich, A. (2019) Space Security and Legal Aspects of Active Debris Removal Froehlich, A. (ed.). *Studies in Space Policy*, 16. doi:10.1007/978-3-319-90338-5.

Gan, J. and Tao, Y. (2015) DBSCAN revisited: Mis-claim, un-fixability, and approximation. *Proceedings of the ACM SIGMOD International Conference on Management of Data*, 2015-May: 519–530. doi:10.1145/2723372.2737792.

Garzaniti, N., Tekic, Z., Kukolj, D., et al. (2021) Review of technology trends in new space missions using a patent analytics approach. *Progress in Aerospace Sciences*, 125: 100727. doi:10.1016/j.paerosci.2021.100727.

Del Giudice, M. (2021) Effective Dimensionality: A Tutorial. *Multivariate Behavioral Research*, 56 (3): 527–542. doi:10.1080/00273171.2020.1743631.

Gruntman, M. (2007) *From Astronautics to Cosmonautics*. North Charleston: Booksurge. Available at: https://books.google.co.uk/books?hl=en&lr=&id=0lpTmrl-D1cC&oi=fnd&pg=PP9&dq=astronautics+and+cosmonautics&ots=YuUuF1SKSK&sig=sdBqB-SVy6nEeAd3tL6mCxJhp5U&redir_esc=y#v=onepage&q=astronautics%20and%20cosmonautics&f=false (Downloaded: 5 June 2024).

Hakima, H. and Emami, M.R. (2018) Assessment of active methods for removal of LEO debris. *Acta Astronautica*, 144: 225–243. doi:10.1016/j.actaastro.2017.12.036.

Han, H., Yu, Y., Wang, L., et al. (2019) Disambiguating USPTO inventor names with semantic fingerprinting and DBSCAN clustering. *Electron. Libr.*, 37 (2): 225–239. doi:10.1108/EL-12-2018-0232.

Heilala, J. (2023) Sustainable operation system for space debris management. *AHFE International*, 115. doi:10.54941/AHFE1004342.

Holgersson, M. and Granstrand, O. (2022) Value capture in open innovation markets: the role of patent rights for innovation appropriation. *European Journal of Innovation Management*, 25 (6): 320–339. doi:10.1108/EJIM-02-2021-0114/FULL/PDF.

Hornik, K., Feinerer, I., Kober, M., et al. (2012) Spherical k-Means Clustering. *Journal of Statistical Software*, 50 (10). doi:10.18637/JSS.V050.I10.

Huang, S.Z., Wu, T.J. and Tsai, H.T. (2016) Hysteresis effects of R&D expenditures and patents on firm performance: An empirical study of Hsinchu Science Park in Taiwan. *Filomat*, 30 (15): 4265–4278. doi:10.2298/FIL1615265H.

Hui, Y. and Liu, Y. (2020) Volumetric Data Exploration with Machine Learning-Aided Visualization in Neutron Science. *Advances in Intelligent Systems and Computing*, 943: 257–271. doi:10.1007/978-3-030-17795-9_18.

IADC (2007) *IADC Space Debris Mitigation Guidelines*. Available at: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf (Accessed: 1 September 2024).

Jaffe, A. and Trajtenberg, M. (2003) Patents, Citations, and Innovations: A Window on the Knowledge Economy. *Computers & Mathematics with Applications*, 45 (10–11): 1774. doi:10.1016/S0898-1221(03)80127-X.

Jain, A.K., Murty, M.N. and Flynn, P.J. (1999) Data clustering. *ACM Computing Surveys (CSUR)*, 31 (3): 264–323. doi:10.1145/331499.331504.

Jakhu, R.S., Nyampong, Y.O.M. and Sgobba, T. (2017) Regulatory framework and organization for space debris removal and on orbit servicing of satellites. *Journal of Space Safety Engineering*, 4 (3–4): 129–137. doi:10.1016/J.JSSE.2017.10.002.

Jeon, J. and Suh, Y. (2019) Multiple patent network analysis for identifying safety technology convergence. *Data Technol. Appl.*, 53 (3): 269–285. doi:10.1108/DTA-09-2018-0077.

Jothi, R., Mohanty, S.K. and Ojha, A. (2021) Gene expression clustering using local neighborhood-based similarity measures. *Comput. Electr. Eng.*, 91. doi:10.1016/J.COMPELECENG.2021.107032.

Kalam, R. and Manikandan, K. (2011) Enhancing K-Means Algorithm for Image Segmentation. *International Conference on Process Automation, Control and Computing*. doi:10.1109/PACC.2011.5979016.

Kang, S.-J., Fan, J., Mao, W., et al. (2019) Evaluating the Optical Classification of Fermi BCUs Using Machine Learning. *The Astrophysical Journal*, 872 (2): 189. doi:10.3847/1538-4357/AB0383.

Kessler, D. (2000) *Critical Density of Spacecraft in Low Earth Orbit: Using Fragmentation Data to Evaluate the Stability of the Orbital Debris Environment*. Available at: https://aquarid.physics.uwo.ca/kessler/Critical%20Density-with%20Errata.pdf (Accessed: 20 March 2023).

Kessler, D., Johnson, N., Liou, J.-C., et al. (2010) The Kessler Syndrome: Implications to Future Space operations. *Advances in the Astronautical Sciences*, 137.

Kessler, D.J. and Cour-Palais, B.G. (1978) Collision frequency of artificial satellites: The creation of a debris belt. *Journal of Geophysical Research: Space Physics*, 83 (A6): 2637–2646. doi:10.1029/JA083IA06P02637.

Kirchherr, J., Reike, D. and Hekkert, M. (2017) Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127: 221–232. doi:10.1016/J.RESCONREC.2017.09.005.

Lai, W., Zhou, M., Hu, F., et al. (2019) A New DBSCAN Parameters Determination Method Based on Improved MVO. *IEEE Access*, 7: 104085–104095. doi:10.1109/ACCESS.2019.2931334.

Ledkov, A.S. and Aslanov, V.S. (2023) Active space debris removal by ion multi-beam shepherd spacecraft. *Acta Astronautica*, 205: 247–257. doi:10.1016/j.actaastro.2023.02.003.

Lee, B., Cho, H.H. and Shin, J. (2015) The relationship between inbound open innovation patents and financial performance: evidence from global information technology companies. *Asian Journal of Technology Innovation*, 23 (3): 289–303. doi:10.1080/19761597.2015.1120497.

Lei, L., Qi, J. and Zheng, K. (2019) Patent Analytics Based on Feature Vector Space Model: A Case of IoT. *IEEE Access*, 7: 45705–45715. doi:10.1109/ACCESS.2019.2909123.

Lens (2023) *Different Types of Patents*. Available at: https://support.lens.org/knowledge-base/different-types-of-patents/ (Accessed: 5 September 2024).

Lens (2024a) *Glossary*. Available at: https://support.lens.org/glossary/ (Accessed: 5 September 2024).

Lens (2024b) *Lens.org*.

Lever, J., Krzywinski, M. and Altman, N. (2017) Points of Significance: Principal component analysis. *Nature Methods*, 14 (7): 641–642. doi:10.1038/NMETH.4346.

Li, J. (2021) Research of Density Based Spatial Clustering of Applications with Noise on TCM Patent Law Evaluation. *2021 IEEE 3rd Eurasia Conference on IOT, Communication and Engineering (ECICE)*, pp. 463–466. doi:10.1109/ECICE52819.2021.9645658.

Li, L. (2015) Space Debris Mitigation as an International Law Obligation: A Critical Analysis with Reference to States Practice and Treaty Obligation. *International Community Law Review*, 17 (3): 297–335. doi:10.1163/18719732-12341307.

Li, M., Yu, J., Yin, Z., et al. (2021a) Research on technological innovation opportunities based on patent analysis and technological evolution. *2021 2nd International Conference on Intelligent Design (ICID)*, pp. 466–471. doi:10.1109/ICID54526.2021.00097.

Li, S., Zhang, X., Xu, H., et al. (2020) Measuring strategic technological strength :Patent Portfolio Model. *Technological Forecasting and Social Change*, 157. doi:10.1016/J.TECHFORE.2020.120119.

Li, Y., Wang, Y., Li, T., et al. (2021b) GNN-DBSCAN: A new density-based algorithm using grid and the nearest neighbor. *Journal of Intelligent & Fuzzy Systems*, 41 (6): 7589–7601. doi:10.3233/JIFS-211922.

Linares, I.M.P., De Paulo, A.F. and Porto, G.S. (2019) Patent-based network analysis to understand technological innovation pathways and trends. *Technology in Society*, 59: 101134. doi:10.1016/J.TECHSOC.2019.04.010.

Liou, J.C. and Johnson, N.L. (2006) Risks in Space from Orbiting Debris. *Science*, 311 (5759): 340–341. doi:10.1126/SCIENCE.1121337.

Madhulatha, T.S. (2012) An Overview on Clustering Methods. *IOSR Journal of Engineering*, 02 (04): 719–725. doi:10.9790/3021-0204719725.

Martin-Lawson, D., Paladini, S., Saha, K., et al. (2024) The cost of (Un)regulation: Shrinking Earth's orbits and the need for sustainable space governance. *Journal of Environmental Management*, 349: 119382. doi:10.1016/J.JENVMAN.2023.119382.

Melnykov, V. and Zhu, X. (2019) An extension of the K-means algorithm to clustering skewed data. *Computational Statistics*, 34 (1): 373–394. doi:10.1007/S00180-018-0821-Z.

Mirjalili, S., Mirjalili, S.M. and Hatamlou, A. (2016) Multi-Verse Optimizer: a nature-inspired algorithm for global optimization. *Neural Computing and Applications*, 27 (2): 495–513. doi:10.1007/S00521-015-1870-7/METRICS.

Miyashita, S., Katoh, S., Anzai, T., et al. (2020) Intellectual Property Management in Publicly Funded R&D Program and Projects: Optimizing Principal–Agent Relationship through Transdisciplinary Approach. *Sustainability*, 12 (23): 1–17. doi:10.3390/SU12239923.

Mohamed, M.M.A., Liu, P. and Nie, G. (2022) Causality between Technological Innovation and Economic Growth: Evidence from the Economies of Developing Countries. *Sustainability*, 14 (6). doi:10.3390/SU14063586.

Murtagh, F. and Contreras, P. (2012) Algorithms for hierarchical clustering: An overview. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, 2 (1): 86–97. doi:10.1002/WIDM.53.

Murtaza, A., Pirzada, S.J.H., Xu, T., et al. (2020) Orbital Debris Threat for Space Sustainability and Way Forward (Review Article). *IEEE Access*, 8: 61000–61019. doi:10.1109/ACCESS.2020.2979505.

Newman, C.J. and Williamson, M. (2018) Space Sustainability: Reframing the Debate. *Space Policy*, 46: 30–37. doi:10.1016/J.SPACEPOL.2018.03.001.

Newman, M., Newman, M., Girvan, M., et al. (2003) Finding and evaluating community structure in networks. *Physical review. E, Statistical, nonlinear, and soft matter physics*, 69 (2 2). doi:10.1103/PHYSREVE.69.026113.

Nishida, S.-I., Kawamoto, S., Okawa, Y., et al. (2009) Space debris removal system using a small satellite. *Acta Astronautica*, 65 (1–2): 95–102. doi:10.1016/j.actaastro.2009.01.041.

Oldham, P. (2022) *The WIPO Patent Analytics Handbook*. Available at: https://wipo-analytics.github.io/handbook/ (Accessed: 28 August 2024).

Oyelade, J., Isewon, I., Oladipupo, O., et al. (2019) Data Clustering: Algorithms and Its Applications. *Proceedings - 2019 19th International Conference on Computational Science and Its Applications, ICCSA 2019*, pp. 71–81. doi:10.1109/ICCSA.2019.000-1.

Paladini, S. and Saha, K. (2023) The quest for sustainability in lower orbit: Conceptual models for space tourism. *International Journal of Tourism Research*, 25 (3): 333–349. doi:10.1002/jtr.2568.

Pantoja, R., Catelan, M., Pichara, K., et al. (2022) Semi-Supervised Classification and Clustering Analysis for Variable Stars. *Monthly Notices of the Royal Astronomical Society*, 517 (3): 3660–3681. doi:10.1093/MNRAS/STAC2715.

Pohlmann, T. and Blind, K. (2014) The Interplay of Patents and Standards for Information and Communication Technologies. *PIK - Praxis der Informationsverarbeitung und Kommunikation*, 37 (3): 189–195. doi:10.1515/PIK-2014-0016.

Pop, G.I., Țîțu, A.M. and Pop, A. (2023) Enhancing Aerospace Industry Efficiency and Sustainability: Process Integration and Quality Management in the Context of Industry 4.0. *Sustainability*. doi:10.20944/PREPRINTS202310.1532.V1.

Radtke, J., Kebschull, C. and Stoll, E. (2017) Interactions of the space debris environment with mega constellations—Using the example of the OneWeb constellation. *Acta Astronautica*, 131: 55–68. doi:10.1016/J.ACTAASTRO.2016.11.021.

Rahim, M.S. and Ahmed, T. (2017) An initial centroid selection method based on radial and angular coordinates for K-means algorithm. *2017 20th International Conference of Computer and Information Technology (ICCIT)*, 2018-January: 1–6. doi:10.1109/ICCITECHN.2017.8281801.

Ribeiro, J.R., Pelicioni, L.C., Caldas, I., et al. (2018) Evolution of Policies and Technologies for Space Debris Mitigation Based on Bibliometric and Patent Analyses. *Space Policy*, 44–45: 40–56. doi:10.1016/j.spacepol.2018.03.005.

Saini, S. and Rani, P. (2017) A Survey on STING and CLIQUE Grid Based Clustering Methods. *International Journal of Advanced Research in Computer Science*, 8: 1510–1512. doi:10.26483/IJARCS.V8I5.3616.

Schoffelen, J.M., Hultén, A., Lam, N., et al. (2017) Frequency-specific directed interactions in the human brain network for language. *Proceedings of the National Academy of Sciences of the United States of America*, 114 (30): 8083–8088. doi:10.1073/PNAS.1703155114.

Schubert, E., Sander, J., Ester, M., et al. (2017) DBSCAN Revisited, Revisited. *ACM Transactions on Database Systems (TODS)*, 42 (3). doi:10.1145/3068335.

Scrucca, L. and Raftery, A.E. (2015) Improved initialisation of model-based clustering using Gaussian hierarchical partitions. *Advances in Data Analysis and Classification*, 9 (4): 447–460. doi:10.1007/S11634-015-0220-Z.

Seitzer, P. and Tyson, J.A. (2021) *Large LEO Constellations, Astronomy, and Space Debris Mitigation*. In T. Flohrer, S. Lemmens and F. Schmitz (eds.). 2021. ESA Space Debris Office. Available at: http://conference.sdo.esoc.esa.int, (Accessed: 5 January 2023).

Seymore, S.B. (2010) The Teaching Function of Patents. *The Notre Dame law review*, 85 (2): 621–669.

Shah, M. and Nair, S. (2015) A Survey of Data Mining Clustering Algorithms. *International Journal of Computer Applications*, 128 (1): 1–5. doi:10.5120/IJCA2015906404.

Smirnov, N.N., Kiselev, A.B., Smirnova, M.N., et al. (2015) Space traffic hazards from orbital debris mitigation strategies. *Acta Astronautica*, 109: 144–152. doi:10.1016/j.actaastro.2014.09.014.

Spector, S., Higham, J.E.S. and Doering, A. (2017) Beyond the biosphere: tourism, outer space, and sustainability. *http://dx.doi.org/10.1080/02508281.2017.1286062*, 42 (3): 273–283. doi:10.1080/02508281.2017.1286062.

Suh, J.W., Sohn, S.Y. and Lee, B.K. (2020) Patent clustering and network analyses to explore nuclear waste management technologies. *Energy Policy*, 146. doi:10.1016/J.ENPOL.2020.111794.

Svotina, V.V. and Cherkasova, M.V. (2023) Space debris removal – Review of technologies and techniques. Flexible or virtual connection between space debris and service spacecraft. *Acta Astronautica*, 204: 840–853. doi:10.1016/j.actaastro.2022.09.027.

Sydorenko, K. and Poltavska, D. (2021) WORLD EXPERIENCE AND MODERN FEATURES OF FINANCING INNOVATION IN THE AEROSPACE SECTOR. *Economic scope*. doi:10.32782/2224-6282/176-3.

Tareq, M., Sundararajan, E.A., Harwood, A., et al. (2022) A systematic review of density grid-based clustering for data streams. *IEEE Access*, PP: 1–1. doi:10.1109/ACCESS.2021.3134704.

Tian, Z. (2019) United States Law and Policy on Space Debris. *Space Security and Legal Aspects of Active Debris Removal*, 16: 155–167. doi:10.1007/978-3-319-90338-5_9.

Tokuda, E.K., Comin, C.H. and Costa, L. da F. (2022) Revisiting Agglomerative Clustering. *ArXiv*, abs/2005.07995. doi:10.1016/J.PHYSA.2021.126433.

Tran, T.N., Drab, K. and Daszykowski, M. (2013) Revised DBSCAN algorithm to cluster data with dense adjacent clusters. *Chemometrics and Intelligent Laboratory Systems*, 120: 92–96. doi:10.1016/J.CHEMOLAB.2012.11.006.

Trump, D.J. (2020) *Executive Order 13914*. Available at: https://www.federalregister.gov/documents/2020/04/10/2020-07800/encouraging-international-support-for-the-recovery-and-use-of-space-resources (Accessed: 1 September 2024).

UN COPUOS (2018) *Guidelines for the Long-term Sustainability of Outer Space Activities*. Available at: https://www.unoosa.org/res/oosadoc/data/documents/2018/aac_1052018crp/aac_1052018crp_20_0_html/AC105_2018_CRP20E.pdf (Accessed: 22 November 2023).

UNOOSA (1967) *Outer Space Treaty*. Available at: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html (Accessed: 1 September 2024).

UNOOSA (1971) *Liability Convention* . Available at: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/liability-convention.html (Accessed: 1 September 2024).

UNOOSA (1975) *Registration Convention*. Available at: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/registration-convention.html (Accessed: 1 September 2024).

Usovik, I.V. (2023) Review of perspective space debris mitigation solutions. *Journal of Space Safety Engineering*, 10 (1): 55–58. doi:10.1016/j.jsse.2022.12.001.

Vani, G. and Hema, Dr.A. (2021) Quantum Statistical Information Grid Clustering for Early Esophageal Adenocarcinoma Detection. *Revista Gestão Inovação e Tecnologias*, 11 (4): 3170–3182. doi:10.47059/REVISTAGEINTEC.V11I4.2360.

Verbandt, Y. and Vadot, E. (2018) Non-patent literature search at the European Patent Office. *World Patent Information*, 54: S72–S77. doi:10.1016/J.WPI.2017.07.001.

Xie, W.B., Lee, Y.L., Wang, C., et al. (2020) Hierarchical Clustering Supported by Reciprocal Nearest Neighbors. *ArXiv*, abs/1907.04915: 279–292. doi:10.1016/J.INS.2020.04.016.

Yeung, K.Y., Fraley, C., Murua, A., et al. (2001) Model-based clustering and data transformations for gene expression data. *Bioinformatics*, 17 10 (10): 977–87. doi:10.1093/BIOINFORMATICS/17.10.977.

Zaloznova, Y. and Chekina, V. (2023) Theoretical principles of financial and economic stimulation of the development of smart industry. *Economy of Industry*, 4 (104): 47–64. doi:10.15407/ECONINDUSTRY2023.04.047.

Zhang, W. and Di, Y. (2020) Model-Based Clustering with Measurement or Estimation Errors. *Genes*, 11 (2). doi:10.3390/GENES11020185.

Zhang, W., Li, F., Li, J., et al. (2023) Review of On-Orbit Robotic Arm Active Debris Capture Removal Methods. *Aerospace*, 10 (1). doi:10.3390/AEROSPACE10010013.

Zhang, Y., Shang, L., Huang, L., et al. (2016) A hybrid similarity measure method for patent portfolio analysis. *J. Informetrics*, 10 (4): 1108–1130. doi:10.1016/J.JOI.2016.09.006.

11 Appendix

11.1 Appendix 1

Parameter	**Description**
Epsilon (EPS, ε)	a parameter that defines the maximum distance between two points for one to be considered as in the neighbourhood of the other. Essentially, it sets the radius around a data point.
Minimum Samples	a parameter that specifies the minimum number of points that must exist within an EPS-radius neighbourhood for a point to be considered a core point (a point that is at the core of a cluster)
Minimum number of Edges	a parameter that specifies the minimum number of connections (lines) to other points that a node requires to be visualised
Minimum Number of Nodes per Cluster	a parameter that specifies the minimum number of nodes that must be present in a cluster for it to be considered a valid cluster in the analysis.

(Lai et al., 2019)

11.2 Appendix 2

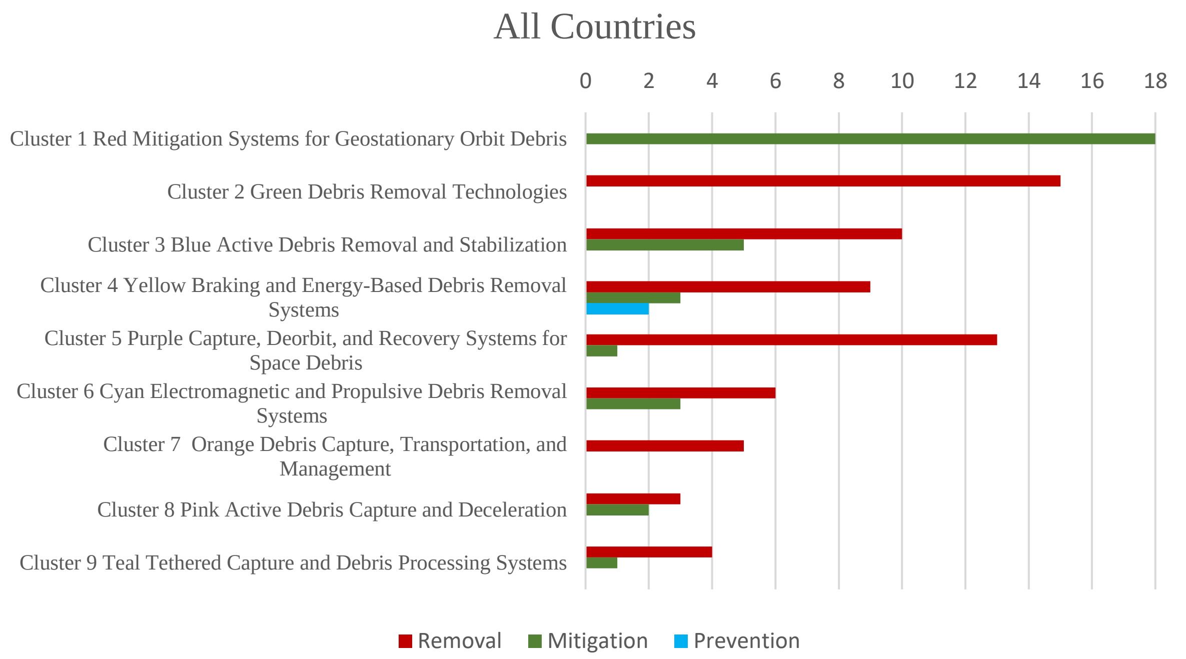
Space Debris Protection Systems			
Category	**Country/Region**	**Cluster**	**Description**
Mitigation			
Space Traffic Management, Debris Intrusion, and Monitoring Systems	EU	Cluster 1 (Red)	Space Traffic Management and Debris Intrusion Warning Systems
	EU	Cluster 3 (Blue)	Space Debris Detection and Measurement Systems
	EU	Cluster 5 (Purple)	Detection and Tracking of Space Debris Using Advanced Sensors
	USA	Cluster 2 (Green)	Space Debris Detection, Tracking, and Modelling Systems

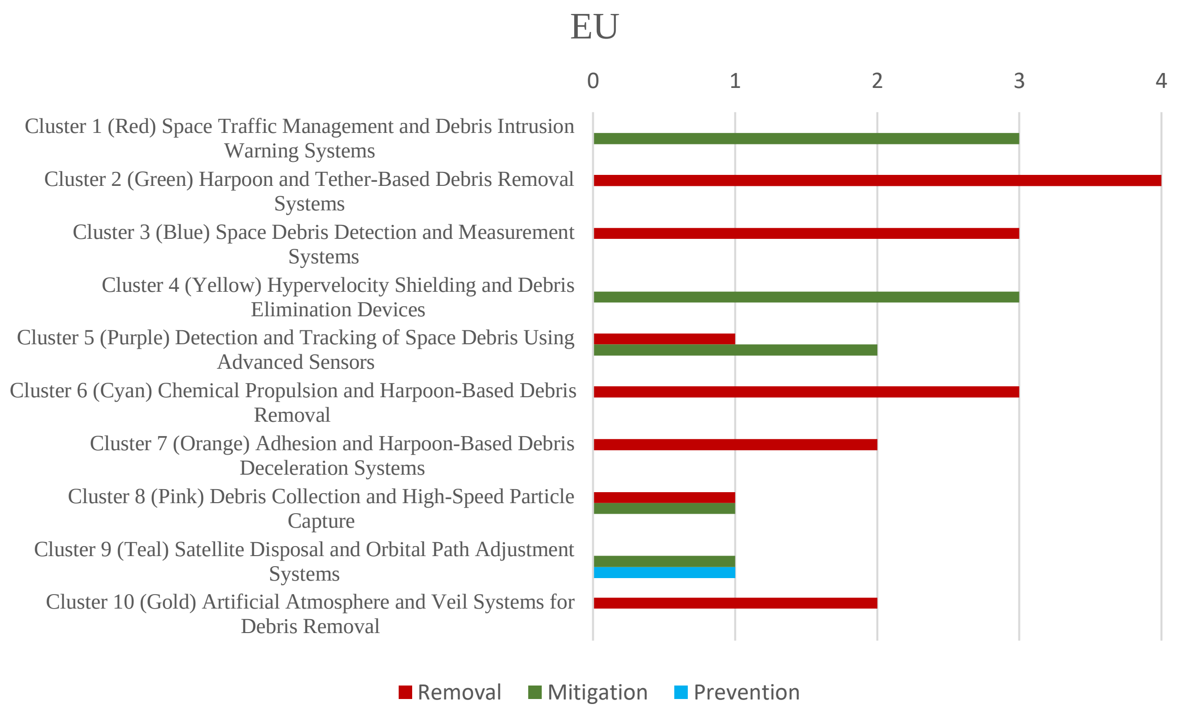
	China	Cluster 3 (Blue)	Space Debris Monitoring and Satellite Maintenance Systems
	Japan	Cluster 4 (Yellow)	Space Debris Detection and Monitoring Systems
	Japan	Cluster 5 (Purple)	Space Debris Detection, Motion Measurement, and Vibration Monitoring Systems
	France	Cluster 1 (Red)	Optical Monitoring Systems for Space Debris Surveillance
	France	Cluster 5 (Purple)	Passive Optical Detection of Space Debris
	France	Cluster 4 (Yellow)	Debris Detection and Monitoring Using Microsatellites
Spacecraft Protection and Shielding Systems	EU	Cluster 4 (Yellow)	Hypervelocity Shielding and Debris Elimination Devices
	USA	Cluster 1 (Red)	Spacecraft Protection and Debris Mitigation Systems
	Japan	Cluster 1 (Red)	Space Debris Shielding, Removal, and Protection Technologies
	UK	Cluster 1 (Red)	Spacecraft Impact Shielding and Debris Protection Systems
	UK	Cluster 2 (Green)	Deployable Heat Shield Systems for Spacecraft
	Russia	Cluster 3 (Blue):	Debris Protection and Removal Systems
Removal			
Debris Removal via Harpoon, Tether, or Similar Capture Systems	EU	Cluster 2 (Green)	Harpoon and Tether-Based Debris Removal Systems
	EU	Cluster 6 (Cyan)	Chemical Propulsion and Harpoon-Based Debris Removal
	USA	Cluster 6 (Cyan)	Debris Interception and Tether Systems
	China	Cluster 1 (Red)	Space Debris Removal and Capture Technologies
	China	Cluster 2 (Green)	Space Debris Removal Systems and Active Debris Management
	Japan	Cluster 2 (Green)	Space Debris Removal and Satellite Deployment Technologies

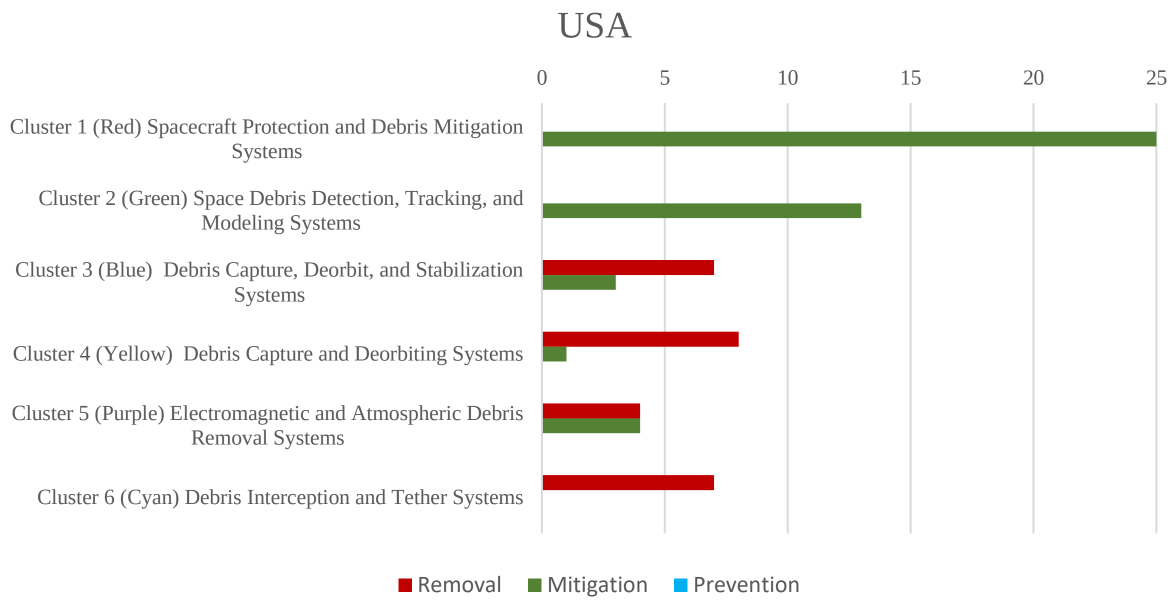
	Russia	Cluster 1 (Red)	Magnetic and Mechanical Systems for Space Debris Collection and Removal
Debris Capture, Collection, and Stabilization Systems	EU	Cluster 7 (Orange)	Debris Collection and High-Speed Particle Capture
	EU	Cluster 8 (Pink)	Adhesion and Harpoon-Based Debris Deceleration Systems
	USA	Cluster 3 (Blue)	Debris Capture, Deorbit, and Stabilization Systems
	USA	Cluster 4 (Yellow)	Debris Capture and Deorbiting Systems
	Japan	Cluster 3 (Blue)	Debris Capture, Deorbit, and Stabilization Systems
Electromagnetic, Atmospheric, and Passive Debris Removal Systems	EU	Cluster 10 (Gold)	Artificial Atmosphere and Veil Systems for Debris Removal
	USA	Cluster 5 (Purple)	Electromagnetic and Atmospheric Debris Removal Systems
	Russia	Cluster 2 (Green)	Electromagnetic and Mechanical Collection Systems for Space Debris Disposal
	China	Cluster 4 (Yellow)	Passive Debris Deorbiting Systems
	France	Cluster 2 (Green)	Capture and Removal of Space Debris Using Flexible System
Prevention			
	France	Cluster 3 (Blue)	Fluid Propulsion and Discharge Systems for Spacecraft End-of-Life and Debris Deviation
	EU	Cluster 9 (Teal)	Satellite Disposal and Orbital Path Adjustment Systems
Unique Clusters			
	Germany	Cluster 1 (Red)	Particle-Based Space Debris Deceleration
	Germany	Cluster 2 (Green)	Asteroid-Derived Construction and Docking Systems
	France	Cluster 6 (Cyan)	Laser-Based Space Debris Removal System
	Russia	Cluster 4 (Yellow)	Destruction and Protection Systems for Space Debris and Natural Objects

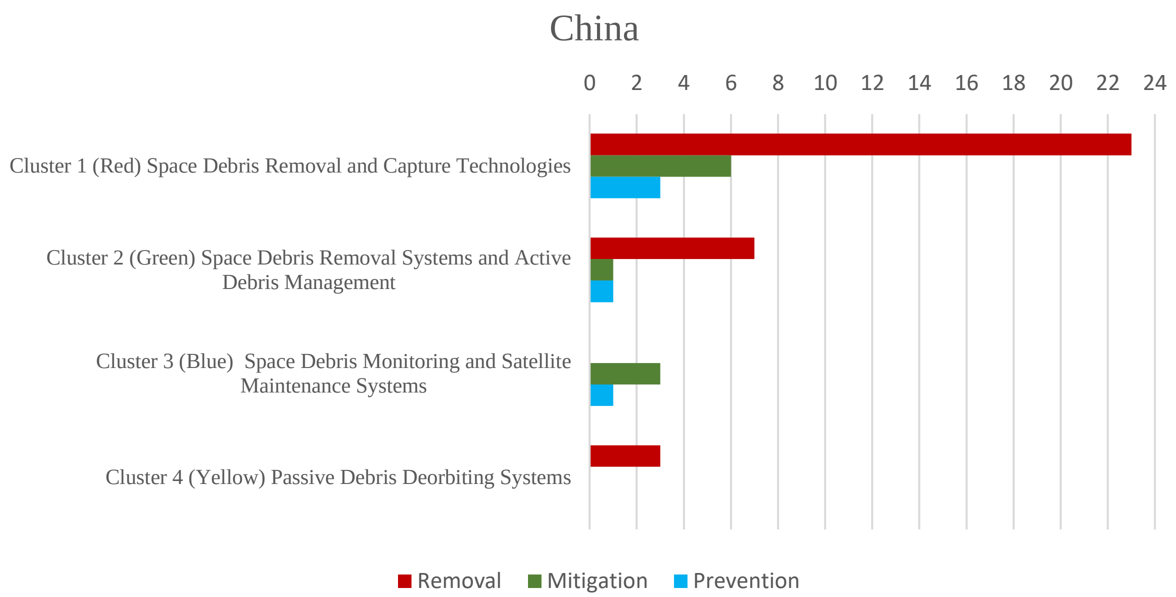
11.3 Appendix 3

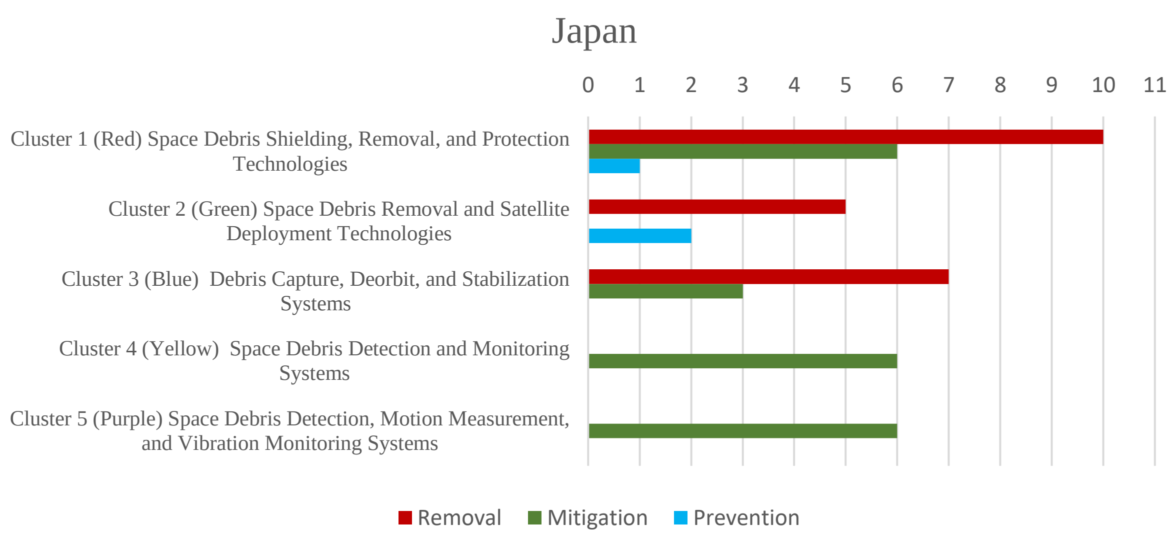
Below you can explore the technological split of each cluster based on their visualisations section 5.2. These visualisations show the cluster name and the split between the three technological focuses.



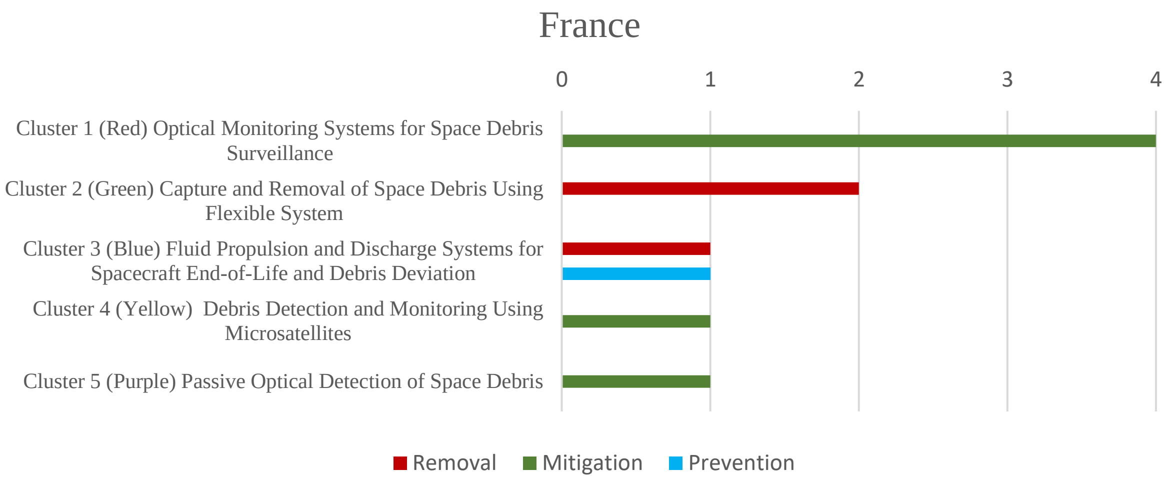


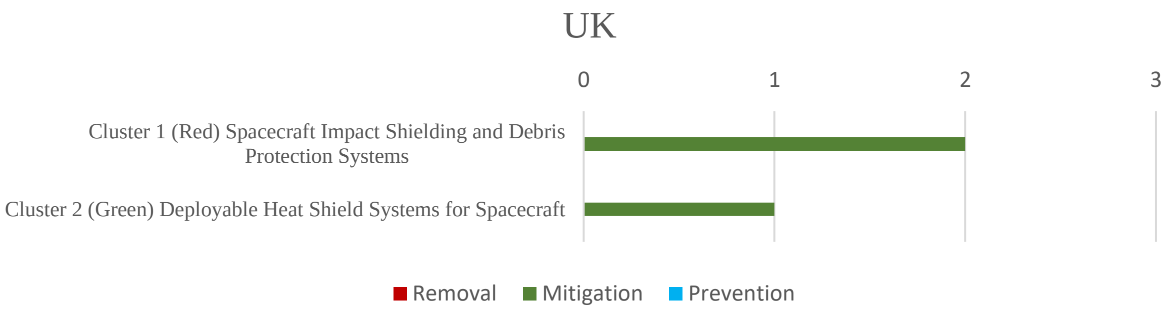

USA
0
5
10
15
20
25
Cluster 1 (Red) Spacecraft Protection and Debris Mitigation Systems
Cluster 2 (Green) Space Debris Detection, Tracking, and Modeling Systems
Cluster 3 (Blue) Debris Capture, Deorbit, and Stabilization Systems
Cluster 4 (Yellow) Debris Capture and Deorbiting Systems
Cluster 5 (Purple) Electromagnetic and Atmospheric Debris Removal Systems
Cluster 6 (Cyan) Debris Interception and Tether Systems
Removal
Mitigation
Prevention

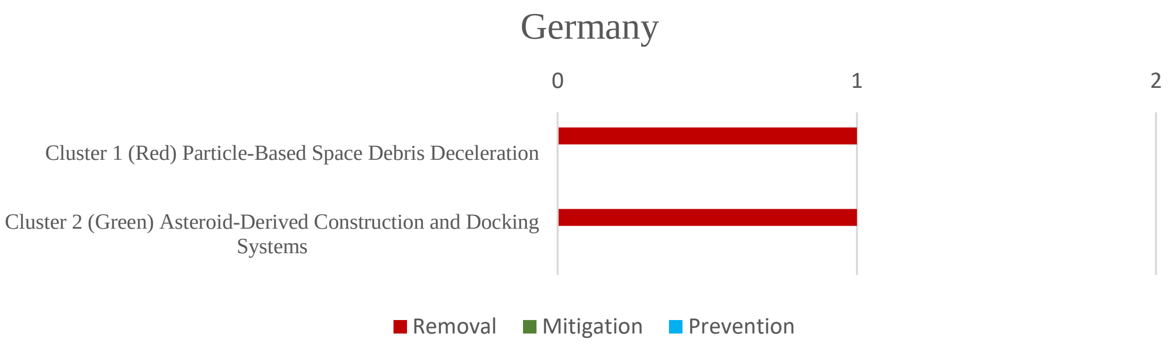

China
0
2
4
6
8
10
12
14
16
18
20
22
24
Cluster 1 (Red) Space Debris Removal and Capture Technologies
Cluster 2 (Green) Space Debris Removal Systems and Active Debris Management
Cluster 3 (Blue) Space Debris Monitoring and Satellite Maintenance Systems
Cluster 4 (Yellow) Passive Debris Deorbiting Systems
Removal
Mitigation
Prevention


Japan
0
1
2
3
4
5
6
7
8
9
10
11
Cluster 1 (Red) Space Debris Shielding, Removal, and Protection Technologies
Cluster 2 (Green) Space Debris Removal and Satellite Deployment Technologies
Cluster 3 (Blue) Debris Capture, Deorbit, and Stabilization Systems
Cluster 4 (Yellow) Space Debris Detection and Monitoring Systems
Cluster 5 (Purple) Space Debris Detection, Motion Measurement, and Vibration Monitoring Systems
Removal
Mitigation
Prevention


Russia
0
1
2
3
4
5
6
Cluster 1 (Red) Magnetic and Mechanical Systems for Space Debris Collection and Removal
Cluster 2 (Green) Electromagnetic and Mechanical Collection Systems for Space Debris Disposal
Cluster 3 (Blue) Debris Protection and Removal Systems
Cluster 4 (Yellow) Destruction and Protection Systems for Space Debris and Natural Objects
Removal
Mitigation
Prevention


France
0
1
2
3
4
Cluster 1 (Red) Optical Monitoring Systems for Space Debris Surveillance
Cluster 2 (Green) Capture and Removal of Space Debris Using Flexible System
Cluster 3 (Blue) Fluid Propulsion and Discharge Systems for Spacecraft End-of-Life and Debris Deviation
Cluster 4 (Yellow) Debris Detection and Monitoring Using Microsatellites
Cluster 5 (Purple) Passive Optical Detection of Space Debris
Removal
Mitigation
Prevention


UK
0
1
2
3
Cluster 1 (Red) Spacecraft Impact Shielding and Debris Protection Systems
Cluster 2 (Green) Deployable Heat Shield Systems for Spacecraft
Removal
Mitigation
Prevention


Germany
0
1
2
Cluster 1 (Red) Particle-Based Space Debris Deceleration
Cluster 2 (Green) Asteroid-Derived Construction and Docking Systems
Removal
Mitigation
Prevention