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Evolution of policies and technologies for space debris mitigation based on bibliometric and patent analyses

Joana Ramos Ribeiro[a,*], Luciele Cristina Pelicioni[a], Ilmo Caldas[a], Carlos Henrique Netto Lahoz[b], Mischel Carmen Neyra Belderrain[a]

[a] Instituto Tecnológico de Aeronáutica (ITA), Praça Marechal Eduardo Gomes, 50, São José dos Campos, SP, Brazil
[b] Instituto de Aeronáutica e Espaço (IAE), Praça Marechal Eduardo Gomes, 50, São José dos Campos, SP, Brazil

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ABSTRACT

The lack of technologies for space debris removal and explicit rules for the use of space are jeopardizing the future of space activities. Thus, the objective of this work was to analyse the current scientific research for space debris mitigation, prevention, monitoring and removal. We used bibliometric and patent analyses from the following databases: Space-track; Celestrack; Derwent; Web of Science.

In this work, the scientific, technological and political actions oriented to space debris mitigation were divided into (1) prevention policies, (2) monitoring and (3) capture. We observed great interest, mainly by the major spacefaring nations, in the development of technologies for detection and removal of space debris from low earth orbit. This increasing interest to develop feasible technologies and effective policies includes governments, space agencies, universities, institutes and private companies, especially from the main spacefaring nations.

1. Introduction

Today's increased dependence on space services has made space activities more complex in terms of number of actors, different types of space launch vehicles, satellites and types of missions.

Each space orbit has some potential for exploration by human-made objects (e.g., GPS and communication services). But Low Earth Orbit (LEO) is the one suffering the greatest impact in recent years. Unfortunately, the legislation of space exploration has not followed space sector evolution and no rigorous update has occurred since 1966, when there were only two spacefaring nations. There are currently about 84 countries and organizations that have their own satellites, involving thousands of companies working in some way with space technology [1].

The lack of debris removal technologies and rules for the use and maintenance of space have made space debris a big “villain” for the space sector, putting at risk the future of space activities such as manned trips, mining and satellite operation. The possibility of another catastrophic event taking place in space worries the main space actors, influencing them to invest in mitigation projects. There is now a wide variety of research fronts searching for feasible solutions to this threat. However, selecting and developing the appropriate technological solutions for each type of debris and the legal-political obstacles are factors that make the cleaning process of the space difficult.

LEO is a region that encompasses objects of several types and from different nations, mainly USA, Russia and China. Each nation has a particular opinion and strategy regarding the removal of debris. In the absence of a coherent multinational strategy, these objects can (and do) fall anywhere on Earth.

In this context, our research applied bibliometric and patent methods in order to analyse the scientific and technological research for space debris mitigation, prevention, monitoring and removal. Some aspects of this study, like actors, research areas and technological trends, were analysed separately.

2. Space debris scenario

In general, space debris is defined as a human-made non-functional space object, ranging from small fragments to non-operational satellites located in Earth orbit or in the process of re-entering in the Earth's atmosphere [2–5]. Some space debris is natural, like meteorites. Some is artificial, like spent launch vehicle stages [6]. Artificial space debris can originate in several different ways: pieces of rocket or satellite; fragments from the collisions between satellites or between satellites with other debris and fragments from war tests or removal tests [2].

According to IADC [5], the reasons for space debris formation are

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[*] Corresponding author.
E-mail address: joana.ribeiro@etep.edu.br (J.R. Ribeiro).

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events such as: a) an explosion caused by the chemical or thermal energy from propellants, pyrotechnics and others; b) a rupture caused by an increase in internal pressure; and c) A break-up caused by energy from collision with other objects.

The total population of space debris has increased by 400% since the first serious accident which occurred in 1961. Since then, about 13 space accidents or events have happened, caused by missile tests, rocket explosions and collision between debris and satellites or between satellites. These have generated more than 6000 pieces of debris [7].

One such case occurred in 2007, after a Chinese test to destroy its own satellite using an anti-satellite missile. This one test generated a significant increase in the amount of space debris. According to Chen [4], another significant event happened in 2009, when an accidental collision between an American military satellite (Iridium 33) and a Russian non-operational satellite (Cosmos 2251), created around 2294 pieces of space debris [8].

2.1. *Evolution of space debris in space*

We used the SPACE-TRACK database to obtain data on operators, types of object (debris or rocket body), orbital situations (decayed or in orbit) and classification codes. We used the CELESTRACK database for data validation. These databases classified the objects as follows:

- Non-functional spacecraft
- Mission-related debris and fragmentation debris
- Rocket bodies are related to launch vehicle stages.

The SPACE-TRACK debris and rocket body categories were used and analysed by the number of objects in orbit, decayed and the total launched.

As shown in Fig. 1, the accumulation of debris is almost five times larger than the number of rocket bodies launched. The analysis of orbital lifetime shows that the average time of debris in orbit is 5.1 years but only 2.3 years for rocket bodies.

Fig. 2 shows the spatial localization of debris in terms of inclination and altitude (using a logarithmic scale for better visualization). This shows a high concentration of space debris from both types of objects in LEO (less than 1,000 km), as well as in Geostationary Orbit (GEO) region (around 36,000 km).

Fig. 3 displays the dispersion of space debris segmented by the main actors responsible: USA, the (Russian) Commonwealth of Independent States (CIS), and China. Together, they are responsible for about 93% of all debris produced to date [8].

Fig. 4 shows the data in more detail for LEO. Debris from the USA permeates a diverse range of inclinations, with greater concentrations in the ranges of 25–40° and 90–100°. The USA is also responsible for the most debris in the altitude range of 100 to 1,000 km. Russia (CIS) concentrates its debris more in the range between 50 and 75° and China presents the highest concentration around 100° and above 750 km.

As of March 2017, a total of 7628 satellites were launched into space [9]. Of this total, 4424 remain in orbit and only 40% are operational. The 2708 non-operational satellites greatly increase the risks of new collisions, forming new space debris clouds or the expansion of existing ones.

The exact number of objects in space is impossible to predict, but is certainly much higher than catalogued, estimated to be in the millions [10,11]. The "Kessler Syndrome" explains the cascade effect that space is subjected to, as new collisions result in a greater number of debris, they increase the likelihood of further collisions. The result is an exponential growth of new debris in space [12].

After the work of Kessler and Cour-Pais [12], several scientific studies about space debris were published, among them the work of Laurance and Brownlee [13], published in the journal *Nature*, entitled "The Flux of Meteoroids and Orbital Space Debris Striking Satellites in Low Earth Orbit".

Eichler [14] expressed his concern that the chain reaction among pieces of debris started long ago. Liou and Johnson [15] showed in their research that, even without any new launches, collisions between the existing satellites will increase the population of large debris faster than the capacity of the atmosphere to remove them.

In the present work, we surveyed papers and patents produced by universities, institutes and companies regarding space debris. Fig. 5 shows the number of papers and patents.

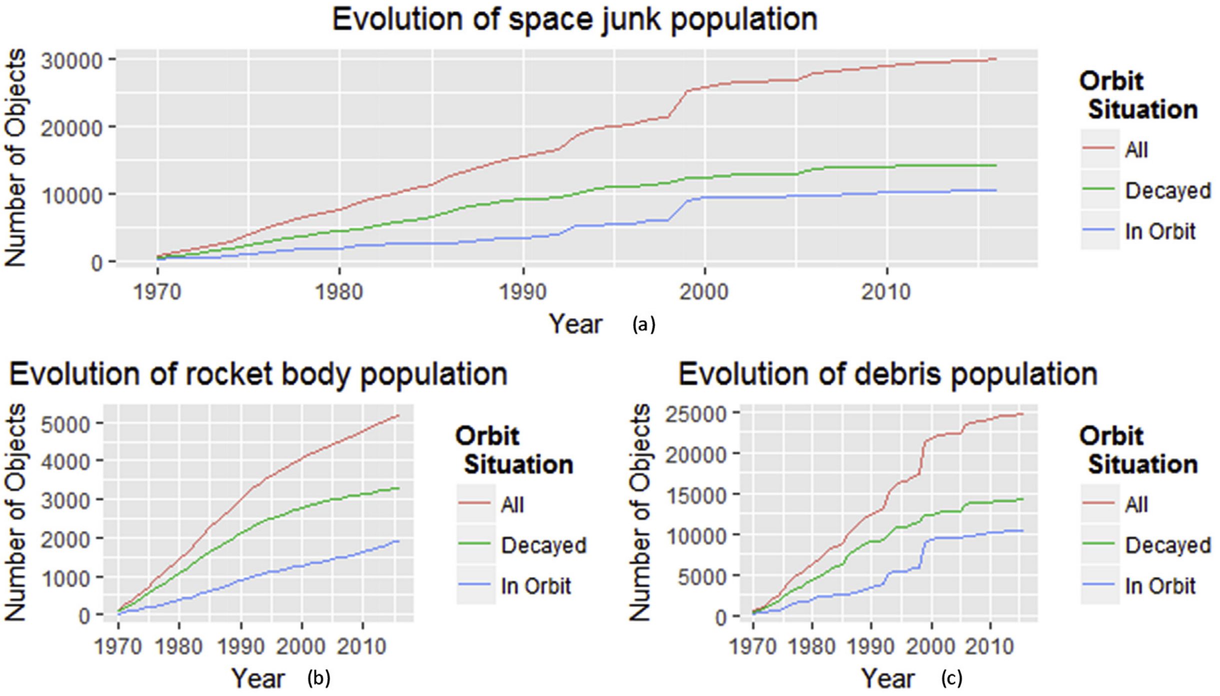

Fig. 1. Evolution of total space junk from debris and rocket bodies.
Data source: SPACE-TRACK, 2017.

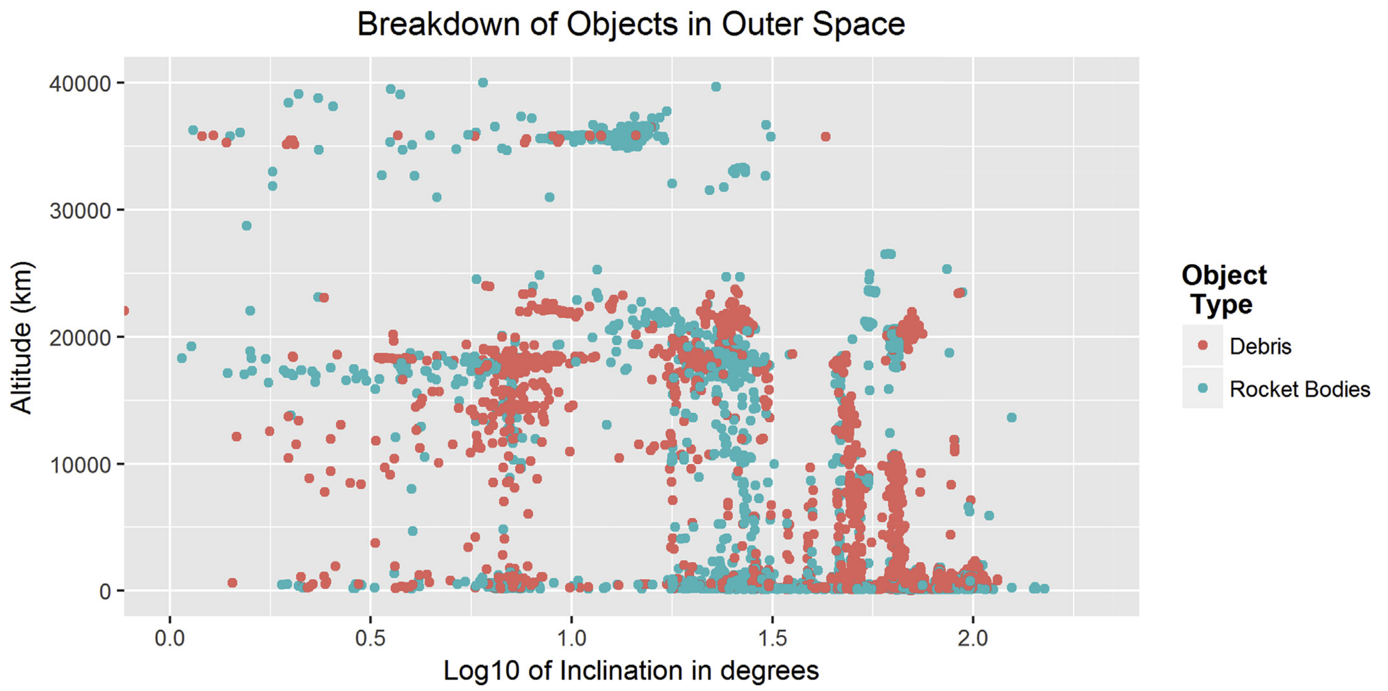

Fig. 2. Space debris localization (altitude *versus* inclination) by type.
Data source: SPACE-TRACK, 2017.

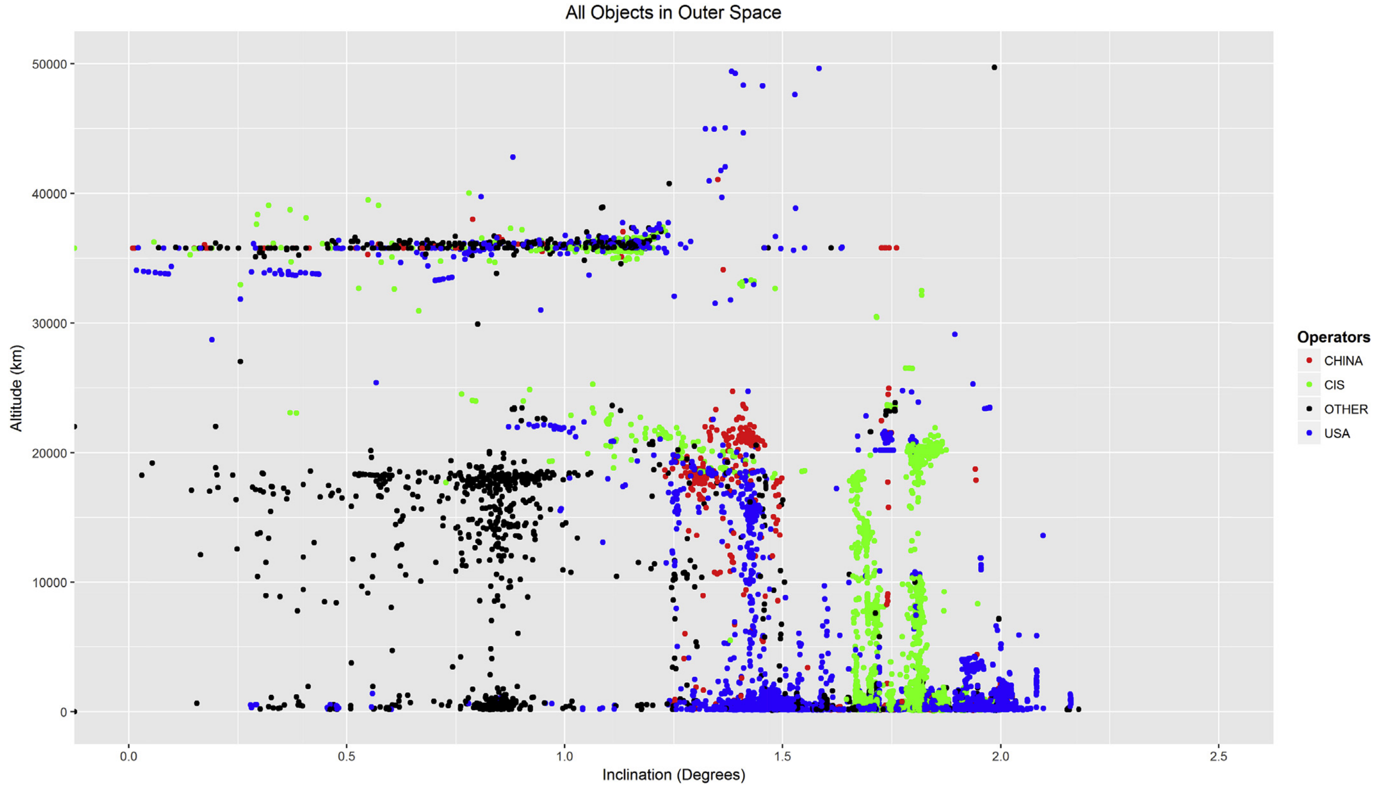

Fig. 3. Space debris localization (altitude *versus* inclination) by country.
Data source: SPACE-TRACK, 2017.

Fig. 5 shows a significant increase in the number of scientific papers, especially after the year of 2000. The number of patents related to space debris, when compared with scientific papers, is inexpressive. However, there are signs of a slight growth in the number of patents since (2010). According to the stages of innovation proposed by Martino [16], this pattern is not unusual. The development of basic research typically precedes technological development. So it is expected that the quantity of patents will also undergo a growth process similar with the growing process of the number of published papers.

Fig. 6 shows the top 22 journals based on the number of publications related to space debris, as well as the number of publications by year. Since the 1990s, there has been a significant increase in the

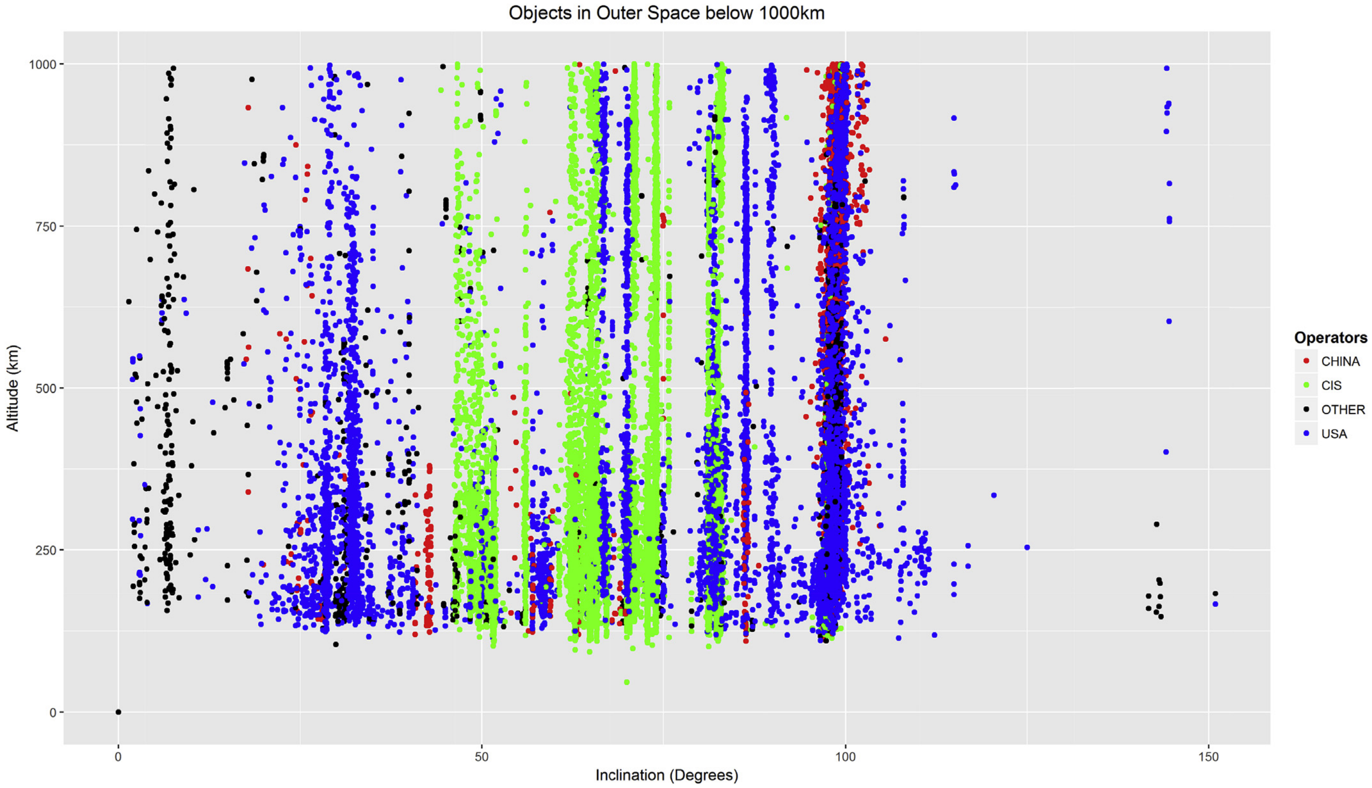

Fig. 4. Space debris localization (altitude *versus* inclination) by country below 1,000 km.
Data source: SPACE-TRACK, 2017.

number of publications related to space debris. The jump that occurred in 2001 resulted from the Third European Conference on Space Debris for which almost half that year's publications were produced. This conference boosted further research and publications in specialized journals.

As shown in Fig. 7a and b, the most patents have been filed by USA, Japan, China, and Russia, whereas the most papers have been published by USA, China, Japan and Germany.

3. Mitigation of the space debris problem

Mitigation consists of a series of man-made interventions aimed at

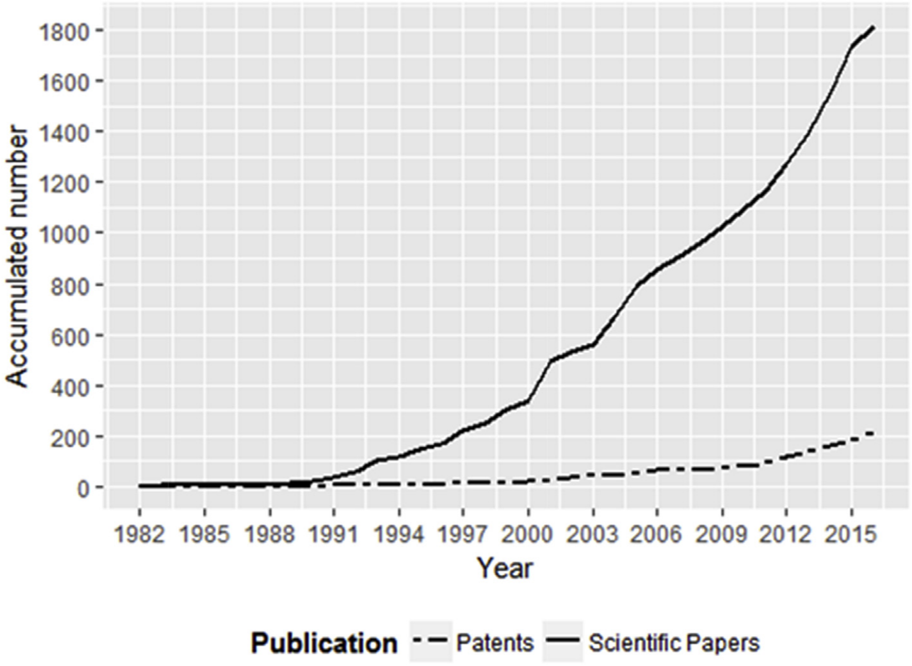

Fig. 5. Accumulated amount of scientific papers *versus* patents.
Data source: Derwent, 2017 and Web of Science, 2017.

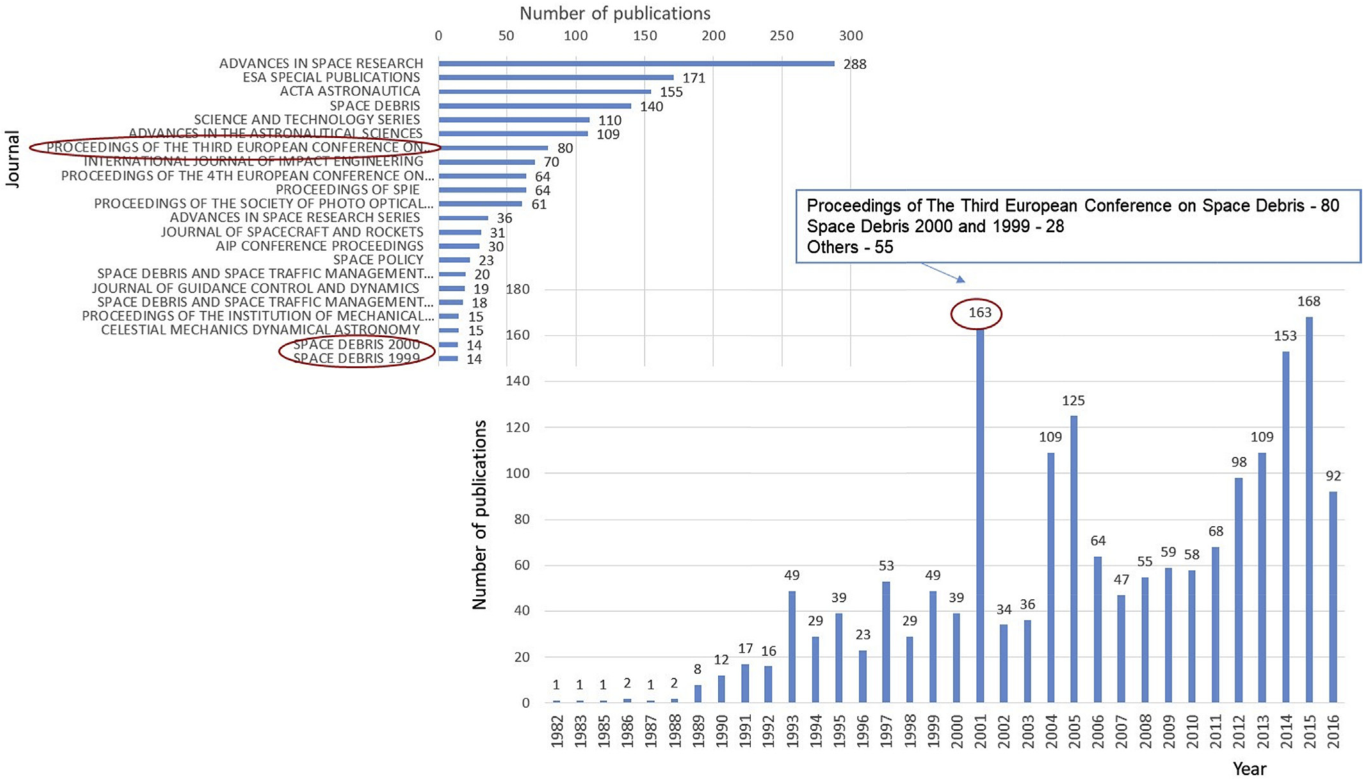

Fig. 6. Top ranked journals for the publication of papers related to space debris over time.

reducing the risk of a potential accident or remedying the impact after an accident. For Rovetto [17], resolving the orbital debris problem entails debris prevention, mitigation and remediation measures, the latter of which involves the development of technologies to physically remove debris.

Space debris mitigation currently follows the recommendations of the Inter-Agency Space Debris Coordination Committee (IADC), by removing non-operational objects from dense regions. According to Ref. [10], space debris is divided into three categories: small (< 5 mm), medium (between 5 and 10 cm) and large (> 10 cm). The larger the object and the higher its speed, the greater the damage caused after an impact.

The bibliometric analysis shows that "mitigation" is among the five most cited words. It is also noticed that this word is strongly related to the actions of monitoring, removal and prevention policies (see Fig. 8).

We divided the scientific, technological and political actions oriented to the mitigation of space debris into three categories that could reduce the space debris growth rate: (1) prevention policies, (2) monitoring and (3) capture.

3.1. Prevention policies

The discussion between spacefaring nations and the first cataloging initiatives of space debris emerged in 1957, which led to the creation of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) in 1958. However, only in 1979 did NASA formally begin to investigate the nature and magnitude of the debris population, creating the Orbital Debris Program Office at the Johnson Space Center (JSC) in Houston, USA.

Ariane 1 explosion in 1986, which produced 492 large pieces of debris in LEO, led to the establishment of the Space Debris Working Group which created the IADC in 1987. The IADC now includes China, Canada, France, Germany, India, Italy, Japan, Korea, Russia, Ukraine, United Kingdom, United States and the ESA. In June 2006, the space agencies of France, Germany, Italy, United Kingdom and ESA all signed the European Code of Conduct for Space Debris Mitigation. While many elements of the European Code of Conduct are similar to those of the IADC and COPUOS, the European document separates the mitigation measures into three categories: management, design and operations.

Kato [18] identified the three primary activities carried out by these organizations as (1) prevention of on-orbit breakups; (2) removal of mission-terminated spacecraft from useful orbit regions; and (3) limiting the objects released during normal operations.

These prevention policies, summarized in Table 1, refer to the main initiatives of some important organizations that are seeking, through different strategies, an effective solution to the alarming growth in space debris. These organizations are studying short-, medium- and long-term mitigation measures that result in the reduction of accident risk in near-Earth space.

In 2011, an important step was taken in the direction of space debris mitigation: the approval and publication of ISO 24113, which defines the primary requirements for space debris mitigation applicable to all elements of unmanned systems launched from Earth [20]. It aims to ensure that spacecraft and launch vehicle orbital stages are designed, operated and disposed in a manner that prevents them from generating debris throughout their orbital lifetime [20].

Despite the fact that India, China or Russia are IADC members, we did not identify any formal organization from them working with debris prevention measures. China, in particular, is becoming an important player with strong scientific and technological contributions in space debris, especially in the areas of debris modelling and numerical simulations.

3.2. Monitoring

Koutchmy and Nitschelm [21] published one of the first papers on space debris monitoring entitled "Optical Detection of Space Debris Using a Large Achromatic Coronagraph". Since then, the space sector has been monitored by several actors. According to Andrade [22], these monitoring activities have achieved good results, with NASA

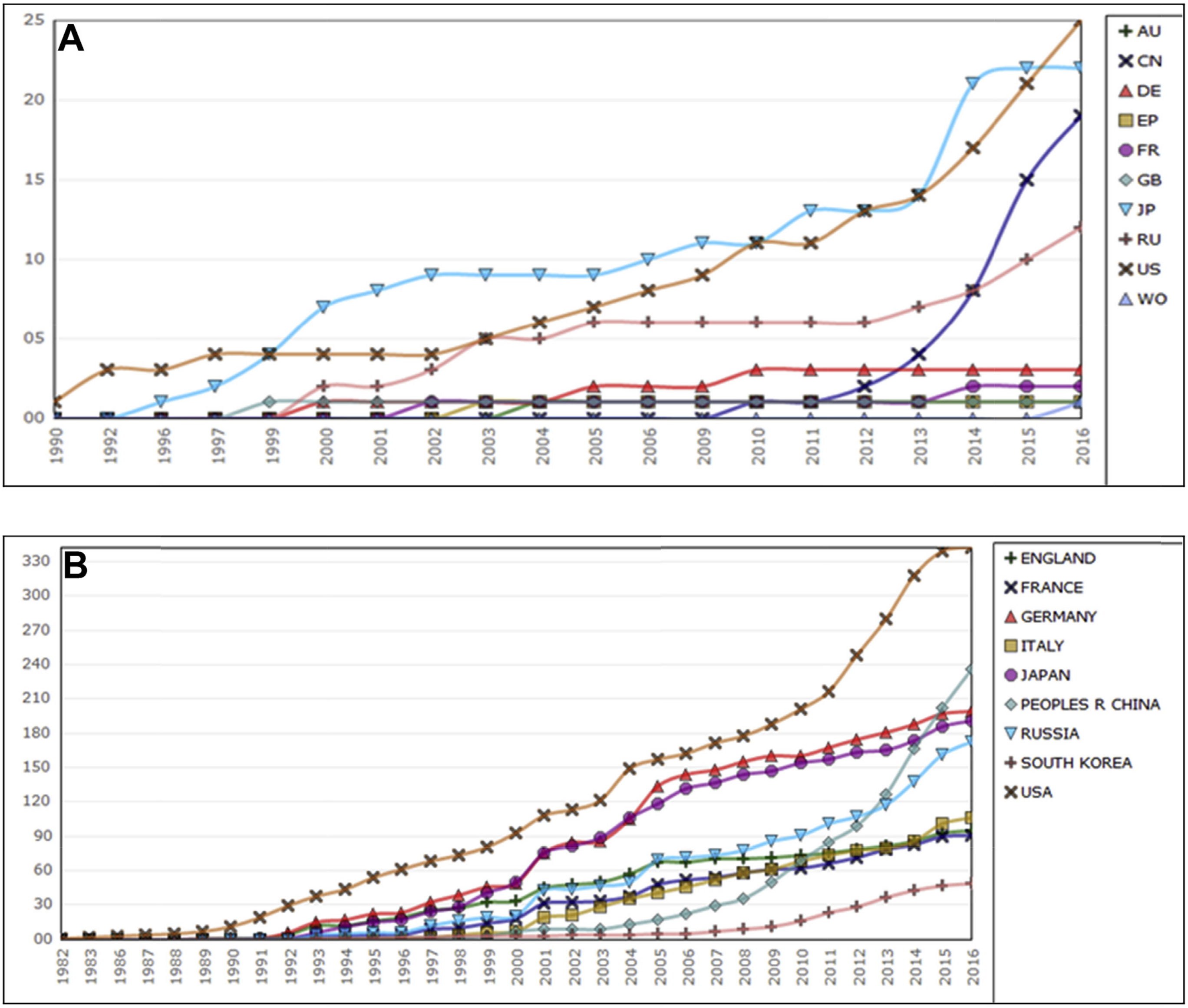

Fig. 7. a - Top ten countries in terms of space debris patent. **b** - Top ten countries in terms of space debris paper.

successfully avoiding eight collisions in 2012 alone.

As reported by Schildknecht et al. [23], countries with major space programs constantly monitor space debris using various detection and tracking technologies. Guidelines focused on space debris management are much less common in countries with limited space activity.

Space debris detection is more complex than tracking due to factors such as high object speed, lack of brightness, altitude, object size, uncertainty of movement, and variety of debris types. Debris detection technologies therefore require very costly high-resolution and high-sensitivity sensors. The cost of developing complex computational algorithms further adds to these costs. Thus, space debris detection is done mostly in short-term campaigns. For example, a campaign may last only five days a year. Or it may be conducted in special cases when there are considerable divergences between expected and obtained results on tracking processes [24]. Thus, it is common for the literature to report only objects larger than 10 cm. Fig. 9 shows space debris monitoring methods.

Until 2013, NASA had catalogued around 17,000 objects over 10 cm [25]. In November 2016, Space Track registered 29,948 objects with dimension over 10 cm, based on database provided by the USA Department of Defence (DoD).

The long duration exposure facility (LDEF) was a space instrument in orbit designed to detect orbital debris in LEO while they collided with the instrument. In agreement with Schildknecht [24], this instrument was able to capture debris up to 5 cm in 5.6 years of operation, but there was controversy about its sustainability and results.

More recently, the updated information on satellites and debris has been performed by ORDEM2000 software, built by NASA Orbital Debris Program Office at Johnson Space Center and by SpaceTrack.org (with weekly and monthly updates).

In spite of the high costs of space debris detection, it is very important given the large investment made by various space actors, since the largest concentration of space debris is in LEO (ISS orbit). As reported by Englert et al. [26] and Andrade [22], there is no expressive number of space debris in GEO.

Space debris tracking methods are cheaper than the detection ones and are constantly used to track spatial objects or as an impact alert.

According to literature, the terms “tracking” and “surveillance” are used for designating space debris tracking processes. The main difference is that the surveillance sensor works only once in a large space area, in a passive way, whereas tracking sensor works in small space area in an active way. In other words, it works with algorithms and

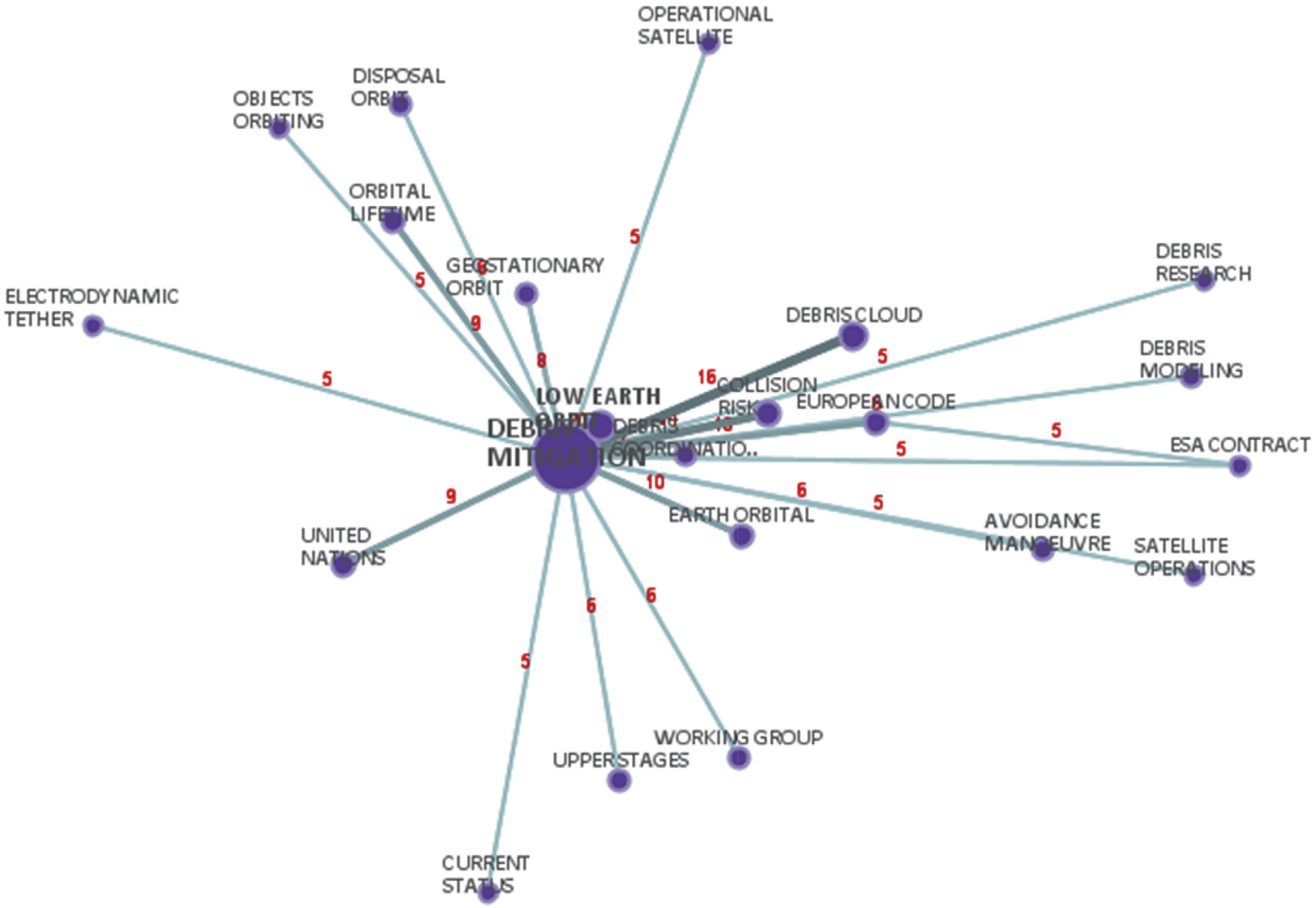

Fig. 8. Bibliometric analysis: the most cited words in scientific papers related to space debris.

systems totally dedicated to the mission [27]. In this paper, the term “tracking” refers to tracking and surveillance practices.

According to Chen and Yi-Ding [28], there are two common ways for tracking objects: captured information in orbit or previous information about the debris. The first and most common monitoring process varies according to the orbital altitude, *i.e.*, it is realized by radars in LEO and by optical sensors in GEO. The radars are positioned on satellites and in bases on the ground. The optical sensors are affixed to bases on the ground and they can be fully dedicated for tracking or other activities.

The second way uses two distinct algorithms for monitoring: (1) generalist and (2) refined information. The generalist algorithm uses surveillance information obtained by radars that monitor a large space area. The refined information algorithm uses precise data from a specific space region. After that, the data obtained from monitoring and predicted by algorithms are compared. New detection campaigns are begun when the results are discrepant [29].

Leitch and Hemphill [30] presented the Canadian Satellite Monitoring System (CSMS), which updates active and inactive satellite mapping, as well as cataloguing pieces of space debris. The data and images obtained are downloaded to a ground station that updates the database. After that, the ground station transmits this information to other institutions such as the American Surveillance Service (US SSN) [31,32].

Table 2 shows the technologies used according to the resolution ability of the objects and the orbit applied.

Some technologies which currently measure small objects in GEO could also be able to operate in LEO. These technologies were developed to capture data, even under illumination influence, distance, size and light reflection. The algorithms used to treat the obtained information need to be robust in terms of faint, moving objects, orbits, physical size and possible detecting. Development of these algorithms is usually coordinated with the data collection instrumentation. For example, the optical sensors of telescopes used in campaigns are constructed according to the data to be captured. However, these technologies are not currently feasible due to their high costs and the fact that the algorithm codes aren't shared beyond the nations that developed them.

As reported by Schildknecht [24], Liquid Mirror Telescope (LMT) is operated in LEO and has observation capacity up to 3 cm; the CCD Debris Telescope (CDT) operates in GEO and has optimal capacity for values between 30 and 40 cm; the ESA 1-m telescope is used for objects from 10 to 15 cm in GEO. These technologies are already in use and are chosen, used and developed according to the conditions, skills, as well as political and technological alliances.

Despite the monitoring realized in sidereal space, events such as autoignition of rocket pieces, control failures and aging satellites inevitably increase the amount of scrap.

3.3. Capture and removal methods

As shown in Fig. 1, about 19,000 tracked pieces of space junk currently exist in orbit. These come mainly from uncontrolled spacecraft, lost equipment, rocket stages, fragments from disintegration or collisions. They create risks to unmanned and manned spacecraft in the space and human activities on Earth. However, there are currently 1738 operational satellites in orbit and around 3000 non-operational satellites, all of which risk generating more space debris.

Table 1
Summary of main prevention measures.

Organization	Main Guidelines
ESA [19]	a) Short-term strategy: prevention of explosions via passivation[a] and prevention of collisions via collision avoidance manoeuvres. b) Long-term strategies: post-mission disposal by removing 5 to10 large objects per year from regions with high object densities and long orbital lifetimes; end-of-life manoeuvre in GEO graveyard and for satellites below 2,000 km — they are programmed to re-enter Earth's atmosphere within 25 years of mission completion and design for demise where space system will fragment during the re-entry on Earth.
IADC [5]	Proposes measures that must be considered during the planning, design, manufacturing, and operationalization phases (launch, mission and elimination) of spacecraft and launch vehicles: (a) Preventing on-orbit break-ups; (b) Removing spacecraft and orbital stages that have reached the end of their mission operations from the useful densely populated orbit regions; and (c) Limiting the objects released during normal operations.
NASA/DOD	Contains three main areas of focus: (a) Measurements: ground-based and space-based observations of the orbital debris environment; (b) Modelling: models development that help to describe and characterize the current and future orbital debris environment; (c) Risk assessment: assesses the risks for all NASA space projects, including human and non-human spaceflight.
ISO 24113 [20]	Proposes 4 main actions: (a) avoiding the intentional release of space debris into Earth's orbit during normal operations; (b) avoiding break-ups in Earth's orbit; (c) removing spacecraft and launch vehicle orbital stages from protected orbital regions after the end of the mission; (d) performing the necessary actions to minimize the risk of collision with other space objects.
European Code Of Conduct For Space Debris Mitigation	The main goals of this code of conduct are: (a) prevention of on-orbit break-ups and collisions of spacecraft; (b) removal and subsequent disposal of spacecraft and orbital stages that have reached the end of the mission operations from the useful densely populated orbit regions; and (c) limitation of objects released during normal spacecraft operations.
Space Debris Mitigation Guidelines of the UN COPUOS	The 7 guidelines consider the planning, design, manufacturing and operation phases of an spacecraft or rocket: (a) to limit debris released during spacecraft/orbital stages operations; b) to minimize the potential for break-ups during operational phases; (c) to limit the probability of accidental collision in orbit; (d) to avoid intentional destruction and other harmful activities; (e) to minimize the potential for post-mission break-ups resulting from stored energy; and (f) to limit the long-term presence of non-operational spacecraft and launch vehicle orbital stages in LEO and GEO.
ITU	Composed by 4 recommendations: (a) as little debris as possible should be released into the GSO (Geosynchronous Orbit) region during the placement of a satellite in orbit; (b) effort should be made to shorten the lifetime of debris in elliptical transfer orbits with the apogees at or near the GSO altitude; (c) a geostationary satellite before the complete exhaustion of its propellant should be removed from the GSO region, remaining in an orbit with a perigee no less than 200 km above the geostationary altitude; (d) the transfer to the graveyard orbit removal should be carried out with particular caution in order to avoid radio frequency interference with active satellites.

[a] Passivation — all latent energy reservoirs of a satellite or orbital stage are depleted to prevent an accidental post-mission explosion.

According to Wang and Savvaris [34], 70% of re-entry objects are uncontrolled so part of this total mass will survive re-entry and impact on the Earth's surface, spreading debris over long ground tracks. To reduce this threat, several reliable scientific methods are being developed for remediation of space debris, particularly in LEO, known as active debris removal (ADR). According to Shan et al. [6], the debris objects in inclination regions 82.5–83.5° and altitudes between 900 and 1,050 km are considered as typical ADR targets.

Many methods for space debris capture and removal have been tested on ground and/or in parabolic flight experiments. One of the greatest challenges is how to capture and remove a non-cooperative target, avoiding the production of even more space debris. So not a single piece of space debris has been removed to date [6].

Capture methods can be divided into two main categories: contact and contactless methods. In the contact category, the methods are Tentacles [35,36], Single robotic arm [37,38], Multiple arms [39], Net

Table 2
Tracking useful technologies and telescopes.
Source: Adapted from Schildknecht [25].

	Less Than 10 cm	Equal to or Greater Than 10 cm
LEO	Narrow field radars Phased array radars Haystack dish antenna Germa 34-m dish radar Liquid mirror telescope (LMT)	NASA CCD Debris Telescope (CDT) MODEST Telescope Tarot Telescope
GEO	Level-1 telescope control AIUB tracking algorithms Declination stripe scanning	CCD Debris Telescope ESA 1-m telescope Masking technique Multi-stripe scanning Orbit determination and catalog correlation

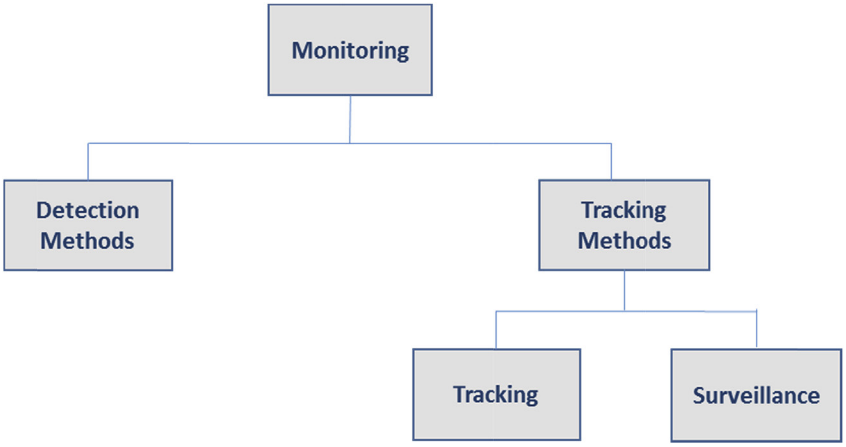

Fig. 9. Space debris monitoring methods.

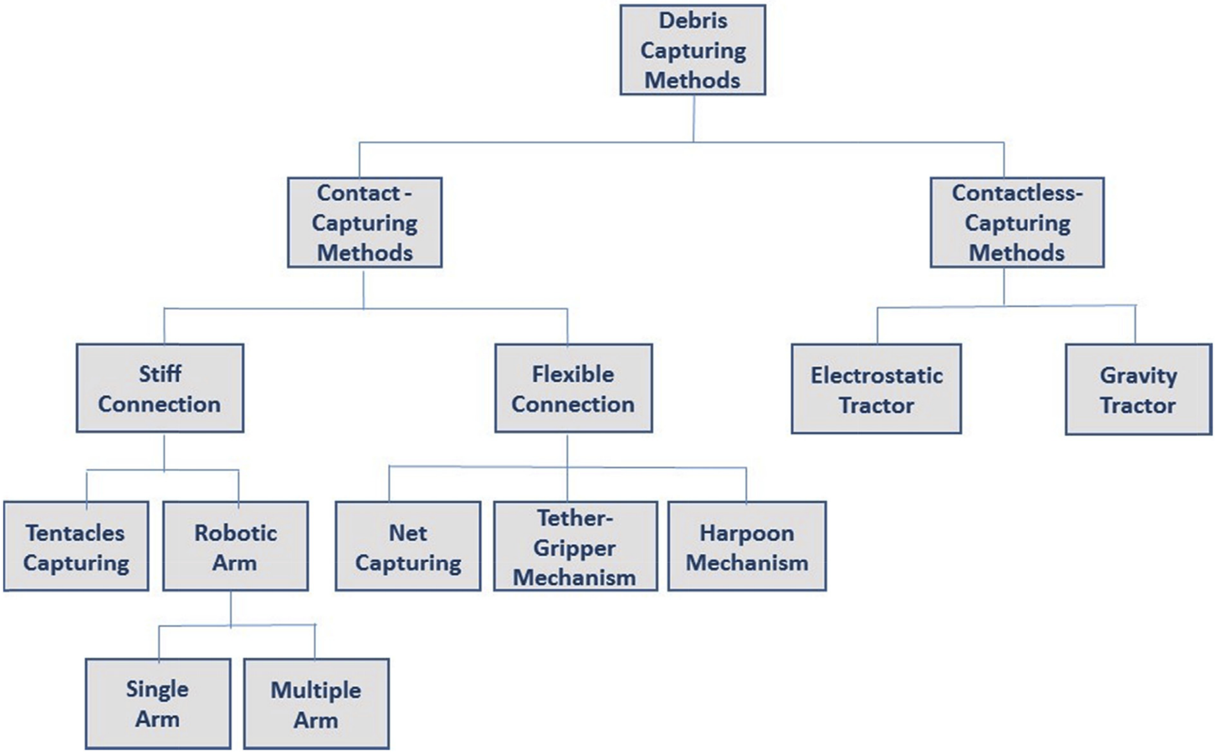

Fig. 10. Space debris capturing methods.
Source: Adapted from Shan et al. [6].

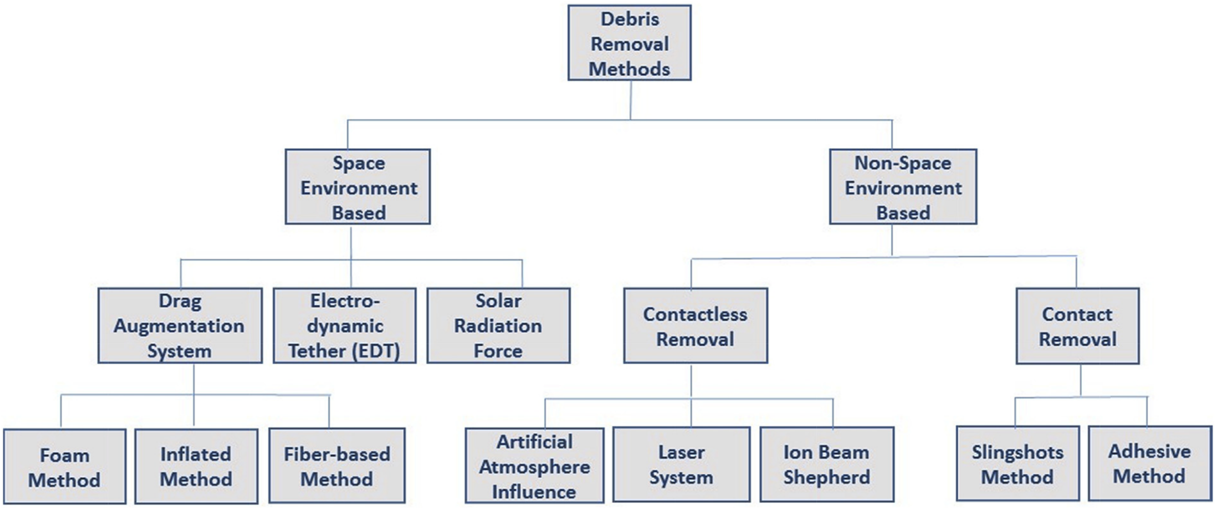

Fig. 11. Space debris removal methods.
Source: Adapted from Shan et al. [6].

capture [35,40–42], Tether gripper [40,43] and Harpoon [44,45]. In the contactless category, the methods are Tractor Electrostatic [46] and Gravity Tractor [47], which use electrostatic forces or gravitation. Fig. 10 shows the existing capture methods.

Shan et al. [6] address advantages and drawbacks in all these options and observe that there is no single capture method which can deal with all kinds of space debris.

Removal methods are different from capture methods since, in some cases, removal is performed after capture. The existing removal methods are shown in Fig. 11. According to the literature, the most pertinent removal methods are the drag augmentation system (DAS) [48–50], electrodynamic tether (EDT) [51], contactless removal methods [52–54] and contact removal methods [55,56].

As for removal policies, the guidelines developed by the IADC and endorsed by the United Nations seek to reduce the growth in space debris but, according to Liou [57], these guidelines represent only a long-term solution.

As reported by IADC [58] in its Terms of Reference, space debris are defined as “all man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional”. This definition was also adopted by the United Nations Committee on the Peaceful Uses of Outer Space [59] in its Space Debris Mitigation Guidelines.

However, according to Weeden [3] and Emanuelli et al. [60], there is no internationally recognized distinction between a functional satellite and non-functional space debris. According to the existing legal

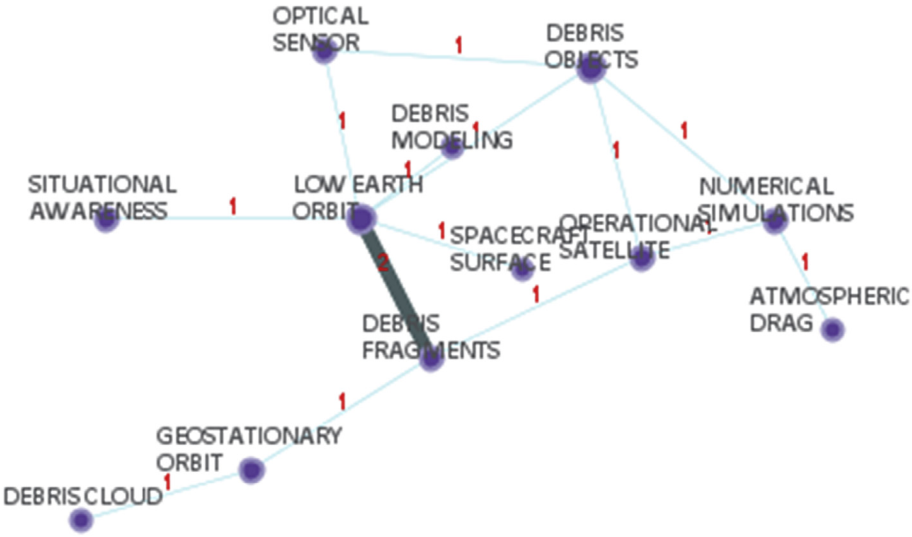

Fig. 12. Association map among keywords related to space debris detection.

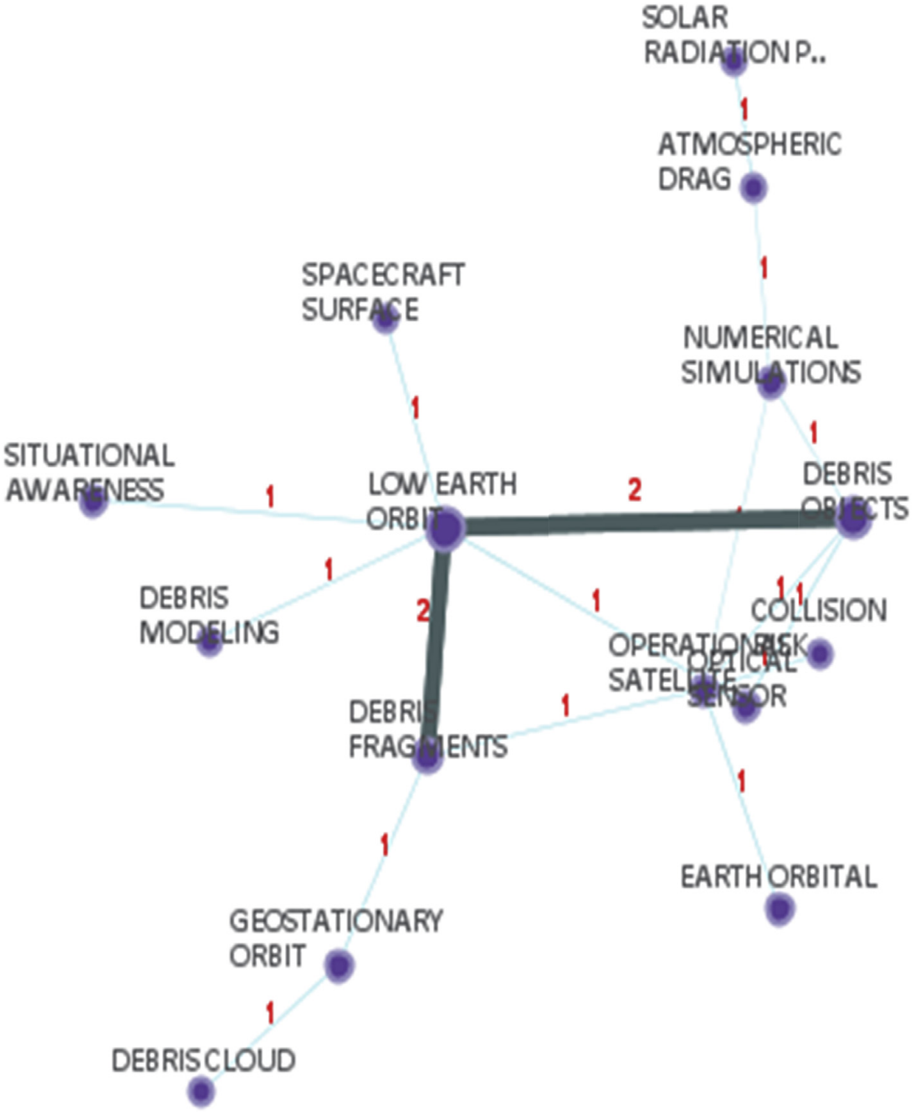

Fig. 13. Association map among keywords related to space debris tracking.

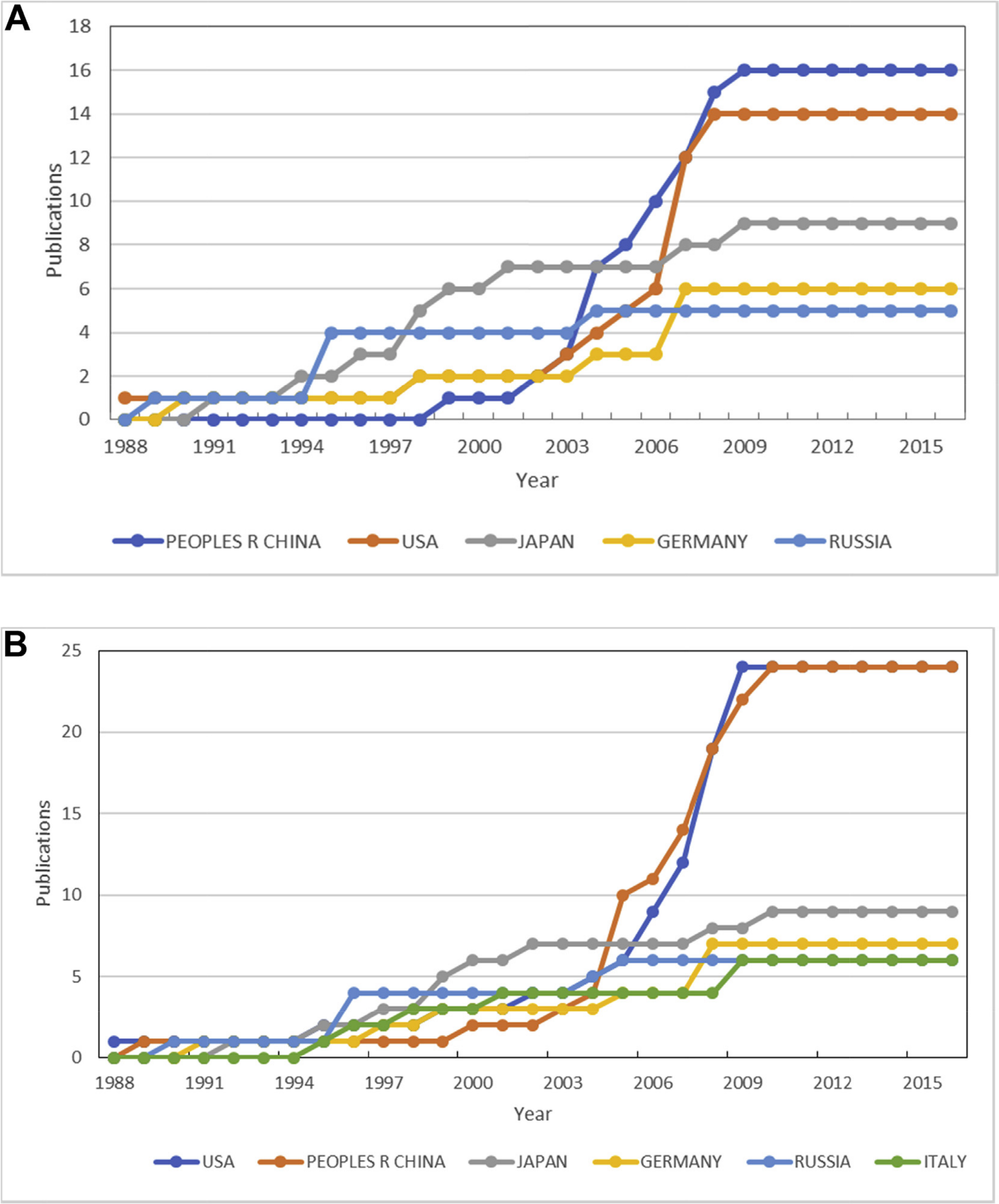

Fig. 14. **a** - Accumulated number of publications related to space debris detection for the countries that most published researches on these themes. **b** - Accumulated number of publications related to space debris tracking for the countries that most published researches on these themes.

regime, both are considered space objects. The lack of this distinction makes it impossible to recognise which objects can be removed. Moreover, it may cause disagreement between states over the status of an object and presents a significant barrier to removal.

4. Bibliometric and patent analyses

In bibliometric analysis, the keyword “space debris” was submitted to the *Web of Science* database, using the available search operators. We selected the records in which the term was present in the titles, abstracts or keywords. The 1941 records obtained through 2016 were analysed using Patent Insight Pro software [61], since such software allowed us to analyse both the patent and the scientific production data. We also used their cleaning tool to eliminate records with incorrect names and duplicates. Thus, four new databases were formed:

- detection (83 records)
- tracking (118 records)
- capture (24 records)
- removal (324 records)

We then identified the main keywords related to space debris capture, removal, detection and tracking.

Figs. 12 and 13 show the keyword association maps related to space debris detection and tracking, respectively. The lines on the association maps represent shared records between the linked nodes. The colour and thickness of the lines are relative to each other and to nodes which have maximum shared records, connected via a thicker and darker line. The red number next to each line represents the number of shared records. Highly-associated items are automatically placed closer to each other.

Fig. 12 shows that the main keywords related to detection were

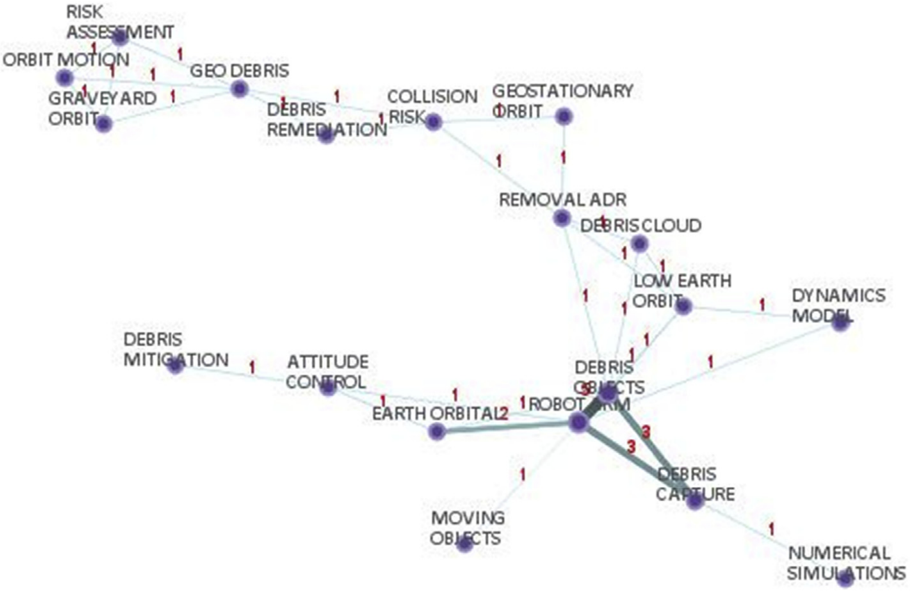

Fig. 15. Association map among keywords related to space debris capture.

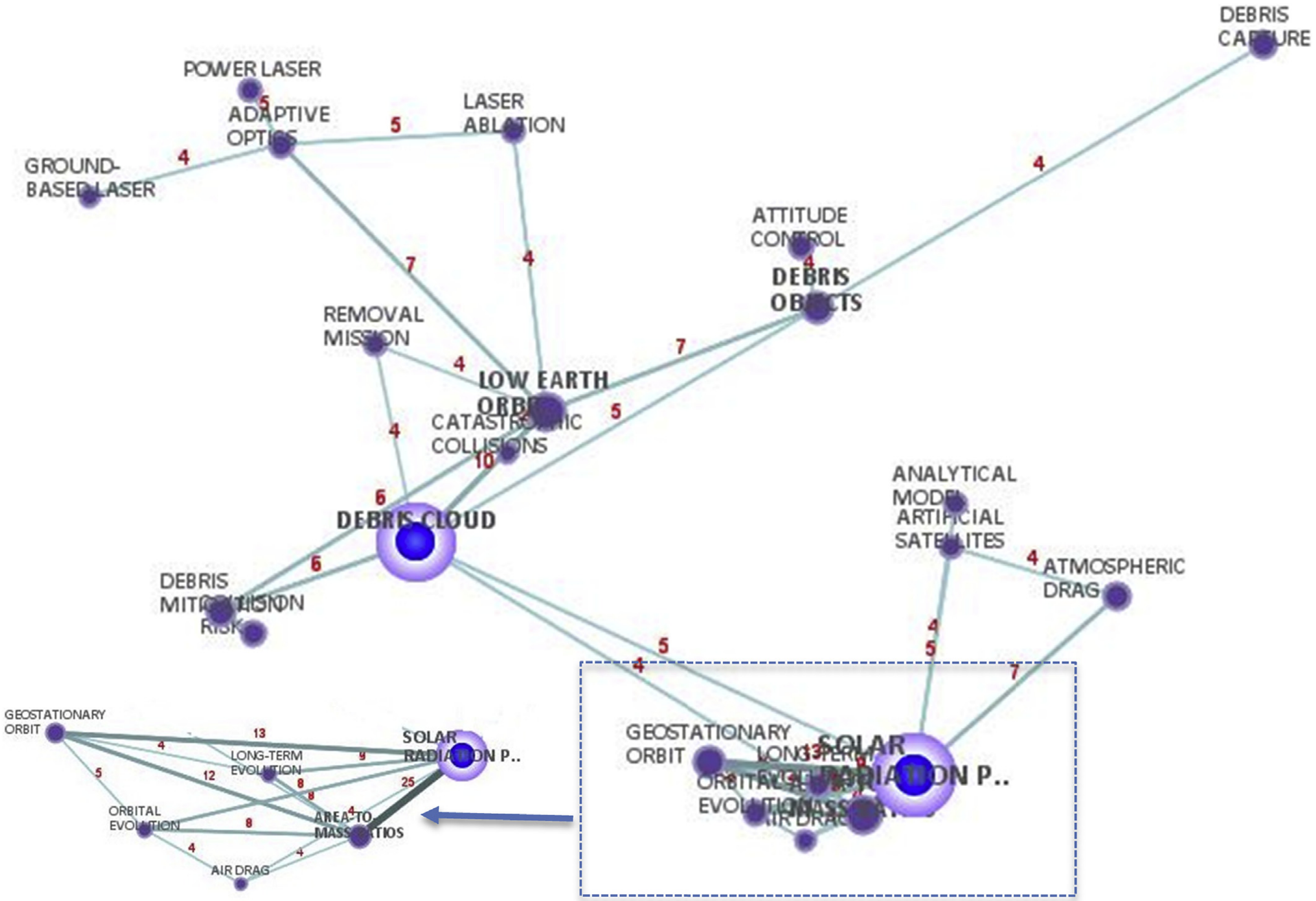

Fig. 16. Association map among keywords related to space debris removal.

"Low Earth Orbit", "Debris Objects", "Debris Fragments", "Operational Satellite", "Spacecraft Surface", "Optical Sensor", "Debris Modelling", "Situational Awareness", "Numerical Simulations", "Atmospheric Drag", "Earth Orbital", "Geostationary Orbit", "Debris Cloud" and "Debris Mitigation". The same keywords were observed for tracking, adding the keywords "Collision Risk" and "Solar Radiation", as shown in Fig. 13.

Figs. 12 and 13 show a strong association among "Debris Objects", "Low Earth Orbit" and "Debris Fragments", suggesting an overcrowding of debris fragments in LEO, and also revealing a preoccupation on

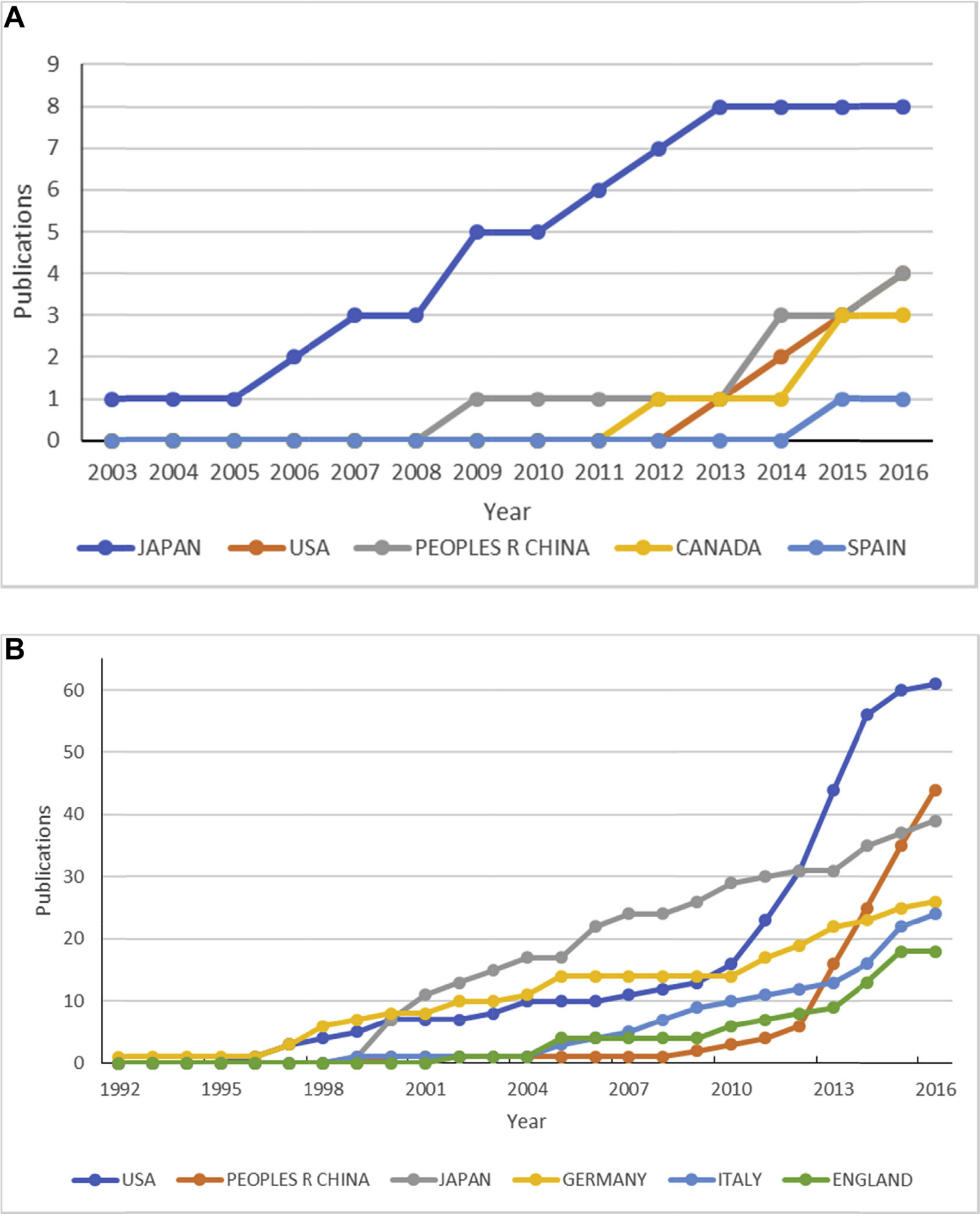

Fig. 17. **a** - Accumulated number of publications related to space debris capture for the countries that most published researches on these themes. **b**- Accumulated number of publications related to space debris removal for the countries that most published researches on these themes.

detecting and tracking this debris cloud.

Based on Figs. 12 and 13, we identified a similarity between detection and tracking procedures. As previously described, detection operations are commonly carried out in campaigns (Observation Campaigns) due their high cost of operation. Thus, research related to technological development have probably been oriented to space debris detection and tracking in LEO due to the high concentration of debris at these altitudes.

Fig. 14 shows that China and the USA are the countries that have more publications in space debris detection (a) and tracking (b).

The main keywords related to capture were “Debris Mitigation”, “Attitude Control”, “Earth Orbital”, “Robot Arm”, “Debris Objects”, “Debris Capture”, “Moving Objects”, “Numerical Simulations”, “Debris Cloud”, “Low Earth Orbit”, “Dynamics Model”, “Removal ADR”, “Geostationary Orbit”, “Collision Risk”, “Debris Remediation”, “Geo Debris”, “Risk Assessment”, “Graveyard Orbit” and “Orbit Motion”. The main keywords related to removal were “Debris Objects”, “Debris Fragments”, “Low Earth Orbit”, “Operational Satellite”, “Large Debris”, “Area-to-mass Ratios”, “Debris Cloud”, “Geostationary Orbit”, “Electrodynamic Tether”, “Orbit Transfer”, “Numerical Simulation”, “Laser Propulsion”, “Laser Ranging”, “Ground-based Laser”, “Pulsed Laser”, “Power Laser”, “Laser Ablation”, “Situational Awareness”, “Collision Risk” and “Solar Radiation Force”.

Fig. 15 shows the keywords highly cited in the literature such as “Robot Arm”, “Debris Objects”, “Debris Capture” and “Earth Orbital”, with a strong association among them. This suggests that the research related to development of space debris capture technologies have been focused on robot arms.

Fig. 16 shows a strong association among the keywords “Debris Cloud”, “Low Earth Orbit”, “Geostationary Orbit”, “Solar Radiation

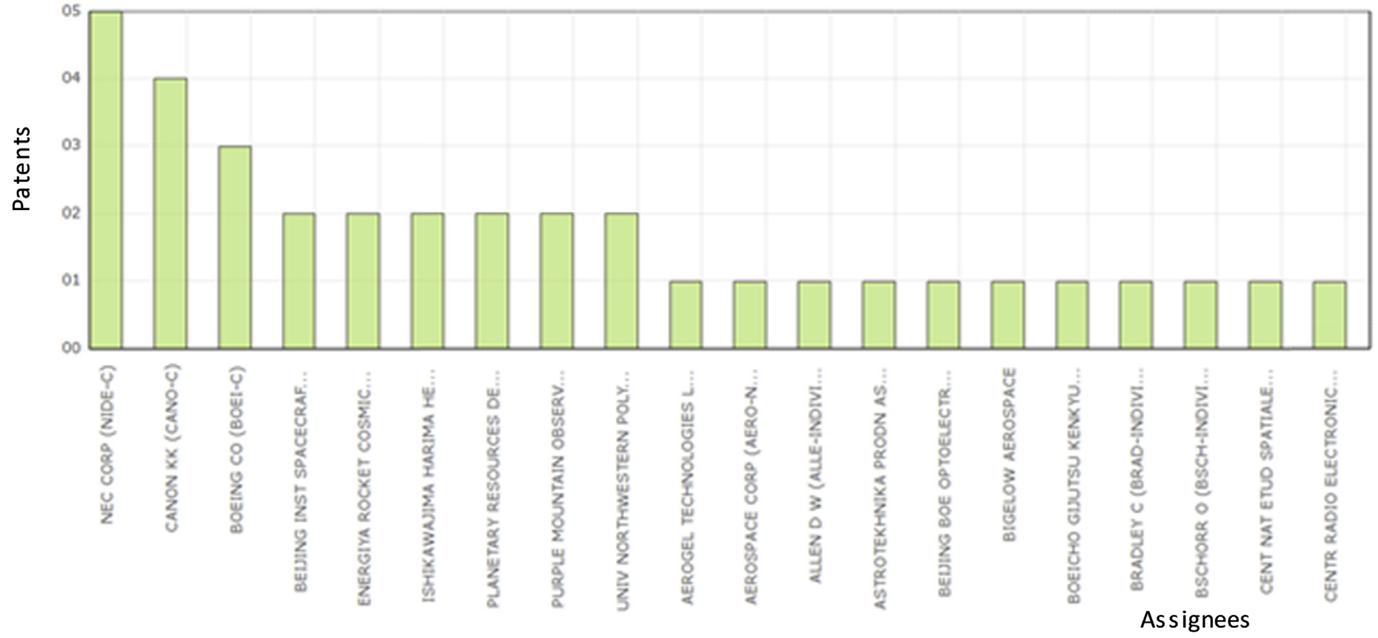

Fig. 18. Main assignees of patents for space debris.

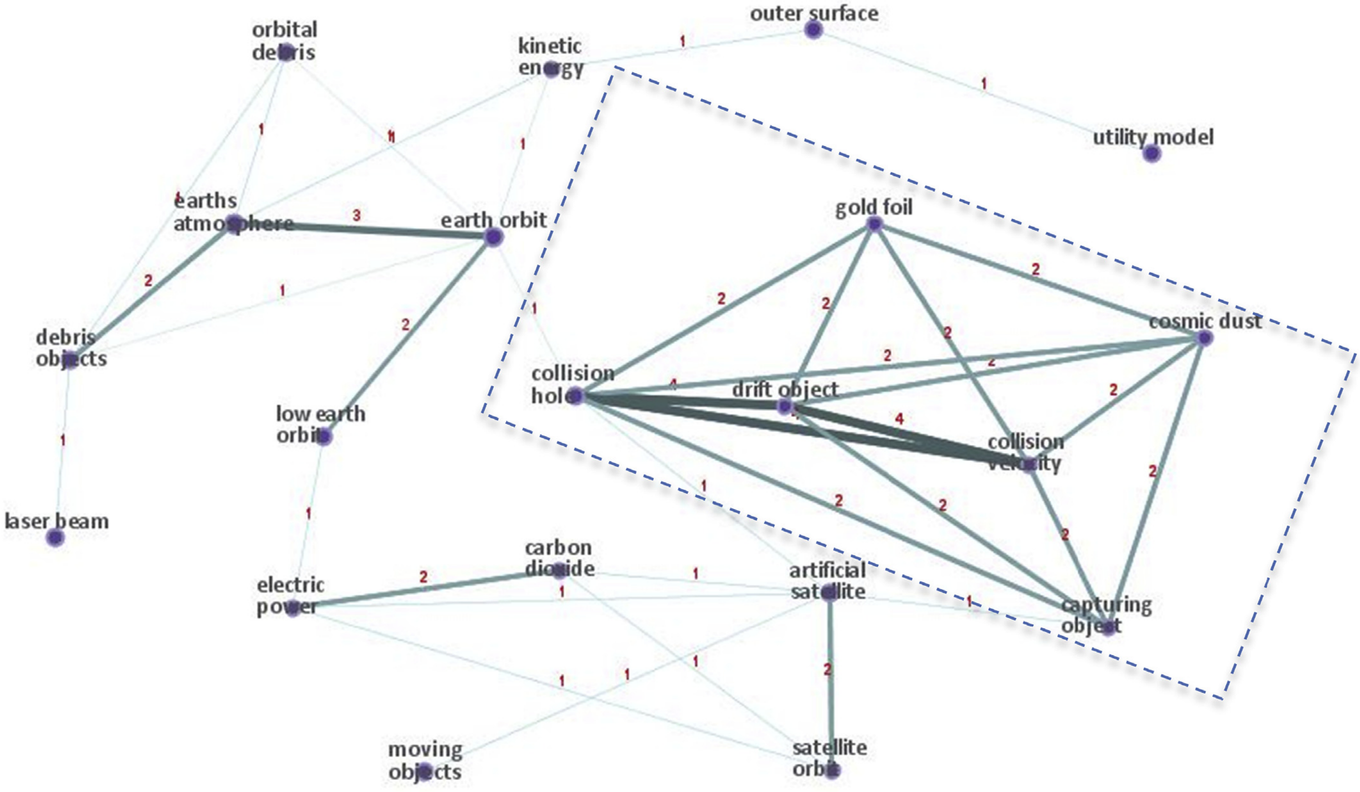

Fig. 19. Association map among keywords related to space debris patent.

Force" and "Area-to-mass Ratios". This suggests that the research related to development of LEO space debris removal technologies have been concentrated on Lasers (laser propulsion, laser-based, pulsed laser, power laser, laser ablation) and EDT. Research related to development of GEO space debris removal have been focused on Solar Radiation Force.

Fig. 17(a) and (b) show a significant increase in the number of publications related to space debris capture and removal since 2000, especially in Japan for capture and USA for removal. Since 2013, China has significantly increased the number of publications, occupying the second position since 2015.

As for patent analysis, the keywords "Space Debris" and "B64G IPC" were submitted to the *Derwent* database (ISI), similarly to previously described bibliometric analysis. The 219 records obtained were also analysed using Patent Insight Pro software [60]. NEC Corporation, Canon and Boeing companies stood out for patent production related to

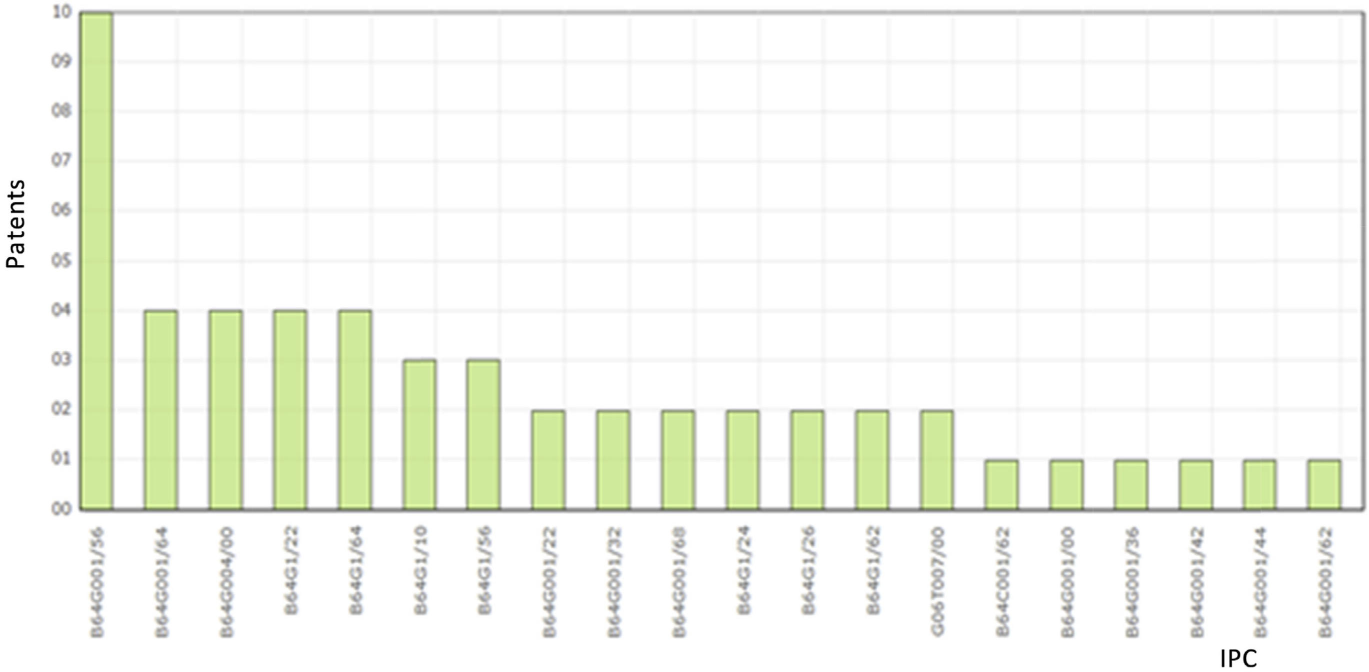

Fig. 20. IPC analysis related to space debris patent.

space debris, as shown in Fig. 18.

Fig. 19 identifies a cluster of keywords (dashed rectangle) with a strong association among them related to natural debris capture mechanisms such as gold foil, cosmic dust, collision hole, collision velocity, capturing object and drift object. The Japanese IHI Corporation is responsible for this grouping of keywords, suggesting a great interest on the development of these technologies. Any keyword related to monitoring methods was identified, but only for removal and capture. The keyword “Utility Model” provides an easy way to enter into the intellectual property system, which is mainly used by China.

Fig. 20 shows the IPC analysis related to space debris patents. The B64G/56 IPC refers to the development of technologies for protection against meteorites. Although this IPC uses the term “Protection Against Meteorites”, its technologies may be also applied to artificial debris.

In general, the patent analysis showed great focus on the development of technologies for space debris detection and removal, especially for natural debris.

5. Conclusions

The continuing increase in space debris is becoming a serious threat to future space activities, especially in the most economical orbital regions. The most prominent space agencies, regulatory bodies and scientists are now focusing their efforts on ways to prevent, control or remove objects that can harm worldwide satellite operations. From the alert created by the Kessler Syndrome, algorithms, sensors, radars, telescopes and smart satellites are being developed to detect and monitor the orbit and size of space debris. In addition, increasing computational processing power is being used to predict the space debris environment. Combined with the use of telescopes (even if they are only used in short time-series campaigns), these have improved monitoring efficiency.

Our bibliometric study indicated that the highly challenging capture and removal of space debris has created strong interest in the development of technologies such as robot arms and lasers. Our study also showed high levels of interest in the development of sensors, modelling and simulation software to detect and monitor fragmented debris in LEO.

Our study also identified a strong scientific movement focused on space debris removal and monitoring starting in 2000. However, our patent analysis showed that the development of technologies is still incipient and focused mostly on natural debris capture. We believe that the risk of the space assets orbiting today, added to the future missions to space, may force the search for mitigation technological solutions in a shorter period of time.

There are currently no clear space debris mitigation regulations agreed between the main spacefaring nations; we believe that this is a crucial next action for the future of space activity.

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