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Taxonomy of LEO Space Debris Population for ADR Selection

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The following paper presents a novel taxonomy method for LEO space debris population. The goal of the method is to provide a new way of classifying low Earth orbit (LEO) space debris objects to support future ADR missions and aid decision making. The method is formulated in two layers. In the first layer, a taxonomic tree is used to identify the main class of an object, based on its most prominent dynamical and physical traits. In the second layer, the hazard of an object and its level of non-cooperativeness are identified and the selection of the most suited ADR capture method, from a safety perspective, is performed. This is done by defining the break-up risk index and levels of non-cooperativeness of targets, based on their passivation state, age, angular rate, physical properties of the capture interface, etc. Examples of application of the developed taxonomy are presented and conclusions are drawn regarding the best methods to be used for the main categories of LEO space debris under investigation for future ADR missions.

1. Introduction

LEO, once considered infinite and void, nowadays is starting to show signs of congestion, due to the human activities in space, which started in 1957 with the launch of the first artificial satellite. A remainder of the gravity of the problem was the first ever recorded, unintentional collision between two satellites, the defunct Russian satellite Kosmos 2251 and the operational US satellite Iridium 33, occurred in 2009 at an altitude of 789 km. This problem was predicted very early by Kessler and Cour-Palais in 1978, which concluded that a substantial number of objects in certain orbits will eventually lead to a self-sustaining cascading process, *the Kessler syndrome*, that would result in a belt of debris around the Earth and exponential growth of the population of space debris [1]. However it has taken the space community some time to react and, up-to-date, only by defining a set of non-binding mitigation measures, in the hope to prevent that process in the near future [2].

Those measures consist mainly in a series of steps to be performed by spacecraft operators in order to:

- reduce the amount of space debris created during a nominal mission,
- minimize potential brake-ups and explosions,
- limit the presence of non-operational spacecrafts and rocket bodies in orbit.

Despite these efforts, studies on the subject showed that the future growth of the space debris population is only to get worse, despite the post-mission disposal (PMD) measures outlined. In particular, the population of objects bigger then 10 cm (considered to be lethal for any active satellite) is expected to rise by 75 % in LEO in the next 200 years, even when considering 90 % PMD compliance of space operators and 100 % suppression of in-orbit explosions [3]. This trend is to be attributed mainly to a total of 24 catastrophic collisions between objects. The same studies show that even in the case of “no-future-launches”, the number of objects is expected to grow due to the on-setting of the Kessler syndrome. Thus, to stabilize the environment and reduce the population of space debris, to a size that it had before the two recent major events (i.e. the collision of Kosmos 2251 and Iridium 33 and the Chinese anti-satellite test (ASAT) on the Fengyun-1C satellite), the in-orbit mass needs to be actively reduced. The natural cleansing effect will not be enough [2]. On the other hand, the projected growth of space debris population in geostationary Earth orbit (GEO) and medium Earth orbit (MEO), even in the worst case scenario, (i. e. in a “business as usual”or “non-mitigation” scenario) is very moderate by comparison [2], which is why the active debris removal (ADR) is considered a priority in the LEO region. For this reason our attention in the rest of this paper will be exclusively dedicated to the LEO region, since it is more needy for active removal of objects in the near future.

A generic ADR mission can be divided mainly into following phases: launch, phasing, far-range rendezvous, close-range rendezvous, capture of a target, stabilization and de-orbiting of the compound.

Among all the phases the capture appears to be the most challenging one, since no spacecraft has ever performed a capture of a non-cooperative target. Moreover, the design of the "capture mechanism" drives the design of the whole chaser spacecraft which is why it is considered in this paper as the most distinctive feature of an ADR mission. Furthermore, given that the removal of objects equal or smaller then 10 cm is as of today non practical [4, 5], those targets will not be considered for the taxonomy. Only large targets (i. e. > 10 cm and capable of generating lethal fragments when impacting an operation spacecraft [6, 4]) are considered in what follows.

Consequently, the number of suitable ADR technologies to tackle those targets is also reduced and among the potential methods the following are considered and divided into two categories: *contact* and *contactless* methods.

Most promising *contact* methods considered in this paper include [7]:

- **robotic-based systems:**
  - manipulator-based: a manipulator system is used to capture a target and stabilize the compound;
  - tentacles/clamp-based: a clamp or a pair of tentacles is used to envelope and embrace a target before capturing it, thus non requiring a dedicated grasping feature on the target;
- **tether-based systems:**
  - net-based: a tethered net is used to envelope and capture a target from a stand-off distance;
  - harpoon-based: similarly to the net system, a tethered harpoon is used to perforate a surface of a target and capture the latter from a stand-off distance.

Most promising *contactless* methods considered in this paper include [7]:

- **plume impingement-based systems** (e. g. ion-based or gas-based): an ion beam or inert gas is used to exchange momentum with the target, thus exerting a net force on it capable of "capturing" it from a stand-off distance.

They all have advantages and disadvantages but none of them can tackle every type of target. Therefore, choosing one ADR method over another, in the initial stages of the mission planning, is a difficult and time consuming task mainly due to the dimensions of the parameter space describing each method and target object. Moreover, there is no easy way to express the degree of hazard that an object represents for an ADR mission that could be easily grasped by a less technical audience, such as the decision makers. One way of solving this issue would be by providing a proper scientific classification of the space debris population that is able to point out the most suitable ADR method safety wise. This way the parameter space describing each object would be reduced to few significant quantities which would be used to properly identify, group, and discriminate space objects while at the same time providing the information about the most suitable ADR method, safety wise, that could be used to capture it.

In this context, the following paper presents a taxonomy of LEO space debris population, based on the taxonomic scheme developed by Früh, C. et al. in [8], to support ADR decision making and classification of the space debris. The outcome of this research is a method for the classification of LEO space debris population and selection of the most suited ADR method, safety wise, for the selected target.

The structure of the remainder of the paper is as follows: Sec. 2 is dedicated to the definition of the taxonomy and brief review of previous studies of taxonomy of space debris. Sec. 3 presents the developed taxonomic method which is divided into: the formulation of the main LEO space debris classes and degree of hazard that an object poses. Sec. 4 illustrates an application of the proposed taxonomy to some of the most representative objects of the main categories of space debris under investigation for ADR, i. e. intact LEO rocket bodies and spacecrafts. Sec. 5 provides the concluding remarks of the paper and the envisioned future work that will improve the developed method.

2. Background and literature survey

Taxonomy can be defined as: "a system for naming and organizing things, especially plants and animals, into groups that share similar qualities" [9]. Therefore, it consists of grouping objects into *taxa* and giving them a rank in order to create a taxonomic hierarchy. More specifically, in biology it consists of a classification of organisms based on their obvious physical traits or, as in case of a phylogenetic classification, also on their genetic characteristics. This way, one is able to determine the descent of a particular organism and its main traits. The most famous taxonomy is the one developed by the Swedish botanist

Carl Linnaeus (considered the father of the biological taxonomy), known as the Linnaean taxonomy and used to classify organisms and naming them based on a binomial nomenclature.

Taxonomy of space debris is generally done in reveres with respect to the biological taxonomy [8], given that the ancestral decent is generally well known in advance. Nevertheless, the taxonomy of space debris is still a relatively young and unexplored territory, due to the large dimensions of the parameter space and immaturity of almost all the ADR technologies.

Wilkins, M. P. et al. in [10] describe a basis for a resident space objects (RSO) taxonomy, based on the structure of the Linnaean taxonomy. Moreover, they also illustrate an algorithmic approach to the satellite taxonomy based on the open source probabilistic programming language, Figaro. The goal of the framework is to classify and identify without ambiguity the class of an RSO based on observation data, while providing the probability of the correct association [10]. However, the purpose of the framework was not to aid ADR therefore it falls short in classifying the objects according to their principal physical and dynamic characteristics that would be most useful for that purpose. Furthermore, it does not deal with the hazard that objects would pose to an ADR mission. Thus, although the framework could be extended and modified to include those properties, it was determined that it would require quite an effort and therefore was not considered as a basis for our approach.

Früh, C. et al. in [8], on the other hand, describe a phylogenetic taxonomy based on more specific physical and dynamic traits of LEO objects with the goal of identifying their main classes and sources of origin. Moreover, they provide a way of visualizing the main traits of object by means of a concise acronym. However, this framework was also not explicitly developed to aid future ADR missions planning, therefore some of the discerning traits were missing (e. g. the break-up risk index or the existence of a berthing feature), while others were not defined in a rigorous manner, thus leaving space for individual interpretation (e. g. the material parameter). However, it does includes a hazard scale of objects based on their size, velocity and area-to-mass ration (AMR), thus indicating how dangerous an object is for the surrounding population. Therefore, it was considered as a good basis for our own taxonomic method and was refined and extended to include more specific traits (e. g. the risk that an object poses to the mission and its level of non-cooperativeness).

3. Taxonomy formulation

3.1 Method formulation

The taxonomy described in this paper consists of two layers developed to aid the initial mission planning for future ADR missions and provide an easy way to visualize, with an acronym (see Fig. 1), the main characteristics of a target object and hazard that it represents for an ADR effort. The first part of the acronym defined in Fig. 1 with a label "*Debris class*", refers to the first layer of taxonomy and it consists of developing a taxonomic tree of space debris based on the most prominent physical and dynamical characteristics of objects. In fact, every letter in this group refers to a specific characteristic of an object, i. e. **U** stands for *uncontrolled*, **R** for *regularly rotating*, **X** for *regular convex*, **L** for *large* and **lo** for *low area-to-mass ration* (AMR). Already at this stage some conclusions about the most suitable ADR capture method, safety wise, for that class can be made. However, ambiguities are to be expected at this stage given the crude nature of the traits used for the formulation of the taxonomic tree. Nevertheless, it is enough for a more programmatic classification of space debris and can be used to filter classes that are non-economically viable or practical for ADR.

To eliminate the mentioned ambiguities and narrow down the ADR association, a second layer of taxonomy is to be performed, on per object basis, and is indicated in Fig. 1 with a label "*Debris hazard*". It consists of individuating the break-up risk index of an object (indicated in the figure with the number **9**) as well as its level of non-cooperativeness (indicated in the figure with the symbol **1L**) which essentially highlights the hazard that the target represents for its capture based on its: passivation state, age, probability of spontaneous break-up, angular rate, properties of the capturing interface (if any), etc.

3.2 LEO space debris classes formulation

In general, defining a taxonomy of any kind involves the following steps: (a) *collection* of data, (b) *identification* of groups and (c) *classification* of groups [11]. This means that at first all the relevant data about the objects that we would like to classify should be collected. Then, objects should be sorted in groups, based on their most relevant and distinguishing features. Finally, *taxa* should be ranked and ordered to make a taxonomic tree which delineates its ancestral decent and minimum amount of information necessary to positively identify an object [8].

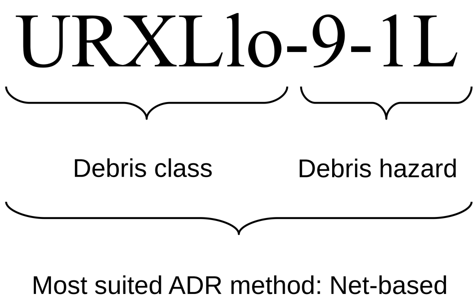

Fig. 1: Example of the taxonomy application to the 1967-045B Cosmos-3M 2nd stage. The acronym identifies: an uncontrolled (U), regularly rotating (R), convex (X), large (L) object with low AMR (lo), having a criticality number (CN) equal to 9 and level of non-cooperativeness equal to 1L (see Table 8 for more details).

Therefore, in this paper the first layer of the taxonomy consists of: (a) defining the main characteristics of LEO objects, (b) building of the taxonomic tree and (c) formulating the classes of LEO objects. The following sections describe those steps more in more detail.

3.2.1 Main characteristics definition

The principle of taxonomic distinction dictates that placing of objects into taxa must be performed without ambiguity [8]. Therefore, it must be done based on their most relevant and distinguishing features. The main characteristics identified as sufficient to classify space debris objects without ambiguity are: its orbital state, attitude state, shape, size and area-to-mass ratio (AMR). Two additional high-level characteristics were also used for completeness but are not explicitly used as distinguishing characteristics between different classes within the taxonomy. They represent the highest groupings of resident space objects around the Earth and are respectively: the **object type** (man-made or natural) and **orbit type** (LEO, MEO GEO, high Earth Orbit (HEO)). The first one is self-explanatory, while the second one is defined in the following manner:

- LEO: for orbits within the 80-2000 km band†.
- MEO: for orbits within the 2000-35,786 km band.
- GEO: for orbits at 35,786 km.
- HEO: for orbits beyond 35,786 km.

†Measured from the surface of the Earth.

The rest of the characteristics is defined as follows.

The **orbital state** illustrates the capability of an object to control its orbital position. It is therefore defined as either controlled or uncontrolled [8]. The *controlled state (C)* indicates an object capable of actively performing maneuvers to maintain certain orbital region within the allowable range of the mission. The *uncontrolled state (U)*, on the other hand, indicates an object whose orbital parameters are expected to change irreversibly over time due to external perturbation forces.

The **attitude state** illustrates the ability of an object to control its attitude. Therefore, it is defined in a similar fashion to the orbital state, with the addition of a third state achievable via a pre-loaded momentum. More in detail, the states identified hereafter are: the actively stabilized, regularly rotating and tumbling [8]. The first state, i. e. the *actively stabilized (S)*, is characteristic of active spacecrafts and indicates the possibility of a spacecraft to actively maintain desired attitude despite external perturbations or dissipative internal forces and torques. The last two states, i. e. the *regularly rotating (R)* and *tumbling (T),* indicate respectively objects having a regular and predictable rotation around one axis, without nutation, and those having an irregular motion, defined usually as a tumbling motion, respectively.

The **external shape** describes the external shape of an object and it has been distinguished in this research as: regular convex (without appendages), regular polyhedral (with appendages) and irregular. This diversification was made from observation of different shapes of existing spacecrafts and objects that could be considered as space debris. The *regular convex shape (X)* refers to objects having mainly cylindrical or spherical shape, typical of some early spacecrafts and rocket bodies. The *regular polyhedral (P)* refers to more conventional spacecrafts, having a cubic shape with appendages. *Irregular shape (I)* is characteristic of space debris that originated form an explosion or an impact.

The **overall size** specifies the mean size of an object and is distinguished in: small, medium and large. More in detail, an object is defined as *small (S)* if its mean size is smaller than 10 cm‡, *medium (M)* if it is between 10 cm and 1 m and *large (L)* if it is bigger than 1 m. The threshold values are set to reflect the sizes of small traceable debris, cubsats and normal and intact spacecrafts (e. g. satellites and rocket bodies) respectively [8, 4, 5].

‡Up to 5 cm, which is the current limit of trackable objects.

The **AMR** expresses the area-to-mass ration of an object based on its mean area and mass. It is used as an alternative to the overall mass of the body, given that it is more informative and concise then the latter characteristic. In this paper, the AMR is divided into three categories based on their values. *Low AMR (LAMR) (lo)* describes an object having an AMR lower then $0.8\,\mathrm{m^2/kg}$, *medium AMR (MAMR) (me)* the one having an AMR within 0.8 and $2\,\mathrm{m^2/kg}$ and *large AMR (LAMR) (hi)* the one having an AMR larger than $2\,\mathrm{m^2/kg}$. The threshold values were chosen in order to reflect typical dimensions of conventional spacecrafts (for LAMR), mission related intact objects, such as multi-layer insulation (MLI) sandwich structures, (for MARM) and fragments of MLI or similar light-weight materials for HARM, respectively [8, 12].

The summary of the main characteristics described before and their concise descriptions can be found for convenience of the reader in the following Table 1.

3.2.2 Taxonomic tree formulation

Using the previously defined characteristics it is possible to build a taxonomic tree of space debris objects (see Fig. 2) which allows us to identify the LEO classes of space debris objects. The branches of the tree are the taxa defined in Table 1, ranked in descending order, as written in the mentioned table. The semi-transparent branches indicate those that are irrelevant for the space debris classification considered in this paper. Therefore, they were not further developed and were included in the tree only for completeness. Furthermore, not all ramifications of the tree were possible, since not all the branches made sense, despite being relevant for the classification. For example, objects having a regularly rotating attitude are most likely to be intact decommissioned spacecrafts or large to medium mission related objects with a well defined shape, i. e. LARM or MARM, not irregular fragments. Thus, this and similar ramifications were omitted.

3.2.3 LEO classes formulation

Following the development of the taxonomic tree, visible in Fig. 2, it was possible to identify the main classes of LEO objects [8]. The result of this step are the 18 classes evidenced in Table 2 which also contains a description of some representative objects of the identified classes.

The main advantage of this kind of classification and notation stands in its concise informative nature that immediately highlights the predominant traits of a class (and thus of a particular object). Moreover, it can be used to filter them out and perform a preliminary association of the most suitable ADR capture method, although with ambiguities and without considering the hazard that individual objects of a class pose to the capture maneuver. For example, the URXLlo class, identifying upper stages and convex spacecrafts with momentum bias, can be tackled by tentacles/clamp-based methods as well as tether-based methods, given that it contains the desired capture characteristics of both methods, i. e. a regular attitude motion and a convex surface. On the other hand, the URPLlo class of objects, identifying polyhedral spacecrafts with momentum bias, has all the traits pointing towards the manipulator-based capture method, i. e.a regular attitude motion and a cubic shape with appendages. However, none of the mentioned classes does include an indication of how dangerous or difficult it would be to actually capture any of the objects within those classes. Moreover, there is no way to tell which of the identified methods is the best if there is a multiple choice.

With this in mind it is obvious that a more detailed analysis of the individual objects within a class is needed. Therefore this is performed in the next layer of taxonomy described hereafter.

To this aim and considering that to stabilize the current space debris environment, predominantly large and massive objects (i. e. having low ARM) will need to be removed in the next 200 years [2], only the classes containing large objects with low ARM are admitted to the next level of taxonomy. Those classes are evidenced by an asterisk (*) in Table 2.

3.3 Debris hazard formulation

The second layer of taxonomy is to be performed on per object basis and consists of individuating: (a) a break-up risk index of an object and (b) its level of non-cooperativeness. The goal of the layer is to identify the hazard and difficulty that an object poses to an ADR capture phase in order to pin-point the most suited ADR capture method for that object, safety wise. This requires the knowledge of more specific physical and dynamical traits of objects, not all of which are available in publicly accessible databases. Moreover, at the time being, there is not one single database[§] containing all of the necessary information, making the automation of this step a difficult approach. Thus, to overcome this limitation and restrict the number of possible permutations, only a limited amount of decisive traits was considered in this layer despite the fact that a bigger parameter space would

[§]At least to best of our knowledge.

Table 1: Main characteristics/taxa of the first layer of taxonomy

Characteristics/Taxa	Definition and their symbols
Object type	Artificial: *man-made object* Natural: *non-man made object*
Orbit type	LEO: *80-2000 km* MEO: *2000-35,786 km* GEO: *at 35,786 km* HEO: $>$ *35,786 km*
Orbital state	Controlled (C): *actively controlled* Uncontrolled (U): *self-explanatory*
Attitude state	Actively stabilized (S): *3 axis stabilized* Regularly rotating (R): *passively controlled/uncontrolled stable (no precession)* Tumbling (T): *irregular attitude motion*
External shape	Regular convex (without appendages) (X): *cylindrical or spherical shapes* Regular polyhedral (with appendages) (P): *regular cubic shapes of spacecrafts* Irregular (I): *self-explanatory*
Size	Small (S): $<$ *10 cm (up to 5 cm)* Medium (M): *10 cm-1m* Large (L): $>$ *1 m*
Area-to-Mass Ratio (AMR)	Low (lo): $< 0.8\,\mathrm{m^2/kg}$ Medium (me): $0.8 - 2\,\mathrm{m^2/kg}$ High (hi): $> 2\,\mathrm{m^2/kg}$

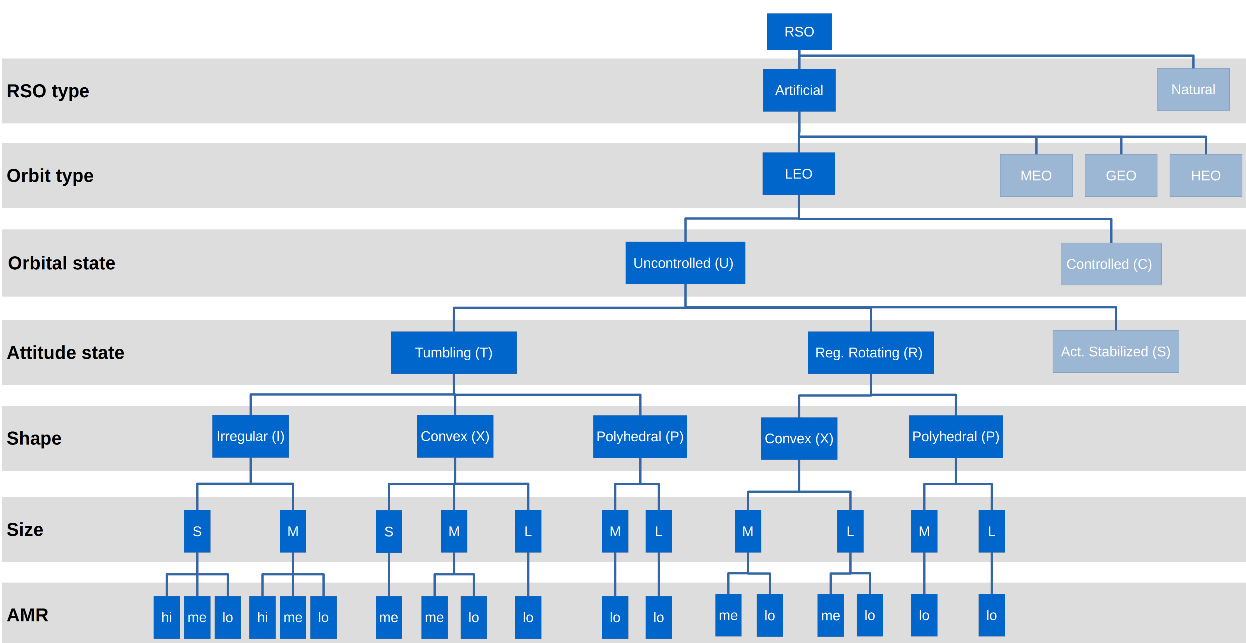

Fig. 2: Taxonomic tree of space debris

Table 2: Main classes of LEO space debris

Acronym of the class	Example objects
Passively stable, intact objects	
URXLlo*	Upper stages/decommissioned spacecrafts with momentum bias
URXMlo	Smaller upper stages/decommissioned spacecrafts with momentum bias
URXLme	Mission related objects with a regular rotation (e. g. covers)
URXMme	Smaller mission related objects with a regular rotation
URPLlo*	Decommissioned spacecrafts with momentum bias
URPMlo	Smaller decommissioned spacecrafts with momentum bias
Intact uncontrolled objects	
UTPLlo*	Generic decommissioned tumbling spacecrafts
UTPMlo	Decommissioned smaller spacecrafts (e. g. cubesats)
UTXLlo*	Tumbling upper stages
UTXMlo	Tumbling, medium-sized mission related objects (e. g. bolts)
UTXSme	Tumbling, small mission related objects with HAMR (e. g. covers)
UTXMme	Tumbling, small mission related objects with MAMR (e. g. covers)
Fragmented uncontrolled objects	
UTIMlo	Medium size, compact fragments
UTIMme	Medium size fragments with MARM
UTISlo	Small size, compact fragments
UTISme	Small size fragments with MARM
UTIMhi	Medium size fragments with HARM
UTIShi	Small size fragments with HARM

yield a more precise results. An automated approach would allow a more precise classification given a bigger solution space but at the time of being is not envisioned at least until efforts are made to populate the current databases with required information¶.

3.3.1 Break-up risk index definition

The break-up risk index of an object is defined by calculating its criticality number (CN) as a product between the severity number (SN) and probability number (PN) of the worst possible failure modes of on-board systems, in accordance with the ESA's standard on Failure modes, effects (and criticality) analysis (see [13]). In this research, it indicates how likely and how dangerous would a spontaneous break-up of an object be should it occur during the capture maneuver.

The worst possible failure mode of passivated objects considered in this study is the rupture of its capture surface. In case of non-passivated objects, a sudden release of pressure or an explosion of a propulsion or power system (i. e. battery packs) are considered.

The definition of SN and PN is done in accordance with the ESA's standard [13] (see Table 3 and 4). The evaluation of those numbers is preformed using a qualitative approach based on engineering judgment, when evaluating failure consequences of worst possible failure modes. Statistical data about in-orbit fragmentations, extrapolated from the ESA's Database and Information System Characterising Objects in Space (DISCOS) database**, was instead used to evaluate the failure probabilities of those modes.

To calculate the break-up risk index, i. e. the CN, it is therefore necessary to first identify if an object has been passivated or not. If it has been passivated, then, no break-up risk exists from on-board stored energy. However, the risk of generating further debris during a capture is not entirely absent, especially if it is to be performed by physically capturing a surface of the object, which might be subject to embrittlement and material fatigue due to the thermal cycling and erosion. Consequently, to calculate the hazard of a passivated object the SN is assumed identical for all the objects of this group and equal to 1, due to limited

¶Or make it publicly available if it is currently existing.

**URL: https://goo.gl/e279ln

Table 3: Severity levels, categories and numbers [13]

Severity			
Level	Category	Failure effects	Number
1	Catastrophic	Loss of system Severe detrimental environmental effects	4
2	Critical	Major damage to interfacing flight systems Major detrimental environmental effects	3
3	Major	Major mission degradation	2
4	Negligible	Minor or negligible mission degradation	1

Table 4: Probability levels, limits and numbers [13]

Probability		
Level	Limits	Number
Probable	$P > 10^{-1}$	4
Occasional	$10^{-3} < P \leq 10^{-1}$	3
Remote	$10^{-5} < P \leq 10^{-3}$	2
Extremely remote	$P < 10^{-5}$	1

environmental effects and mission impact of a possible surface fragmentation due to the embrittlement. The PN on the other hand, is determined by calculating the following linear function, $PN = 0.0025 \cdot yr$, where the variable yr indicates the age (in years) of the target object. The slope of the linear function was calculated considering the initial and final values of PN equal to 10^{-5} and $1.5 \cdot 10^{-1}$, respectively, while assuming that the yr values were, 0 and 59.

If an object has not been passivated, there is a break-up risk that needs to be taken into consideration during a capture maneuver because of the uncertainty of the status of on-board systems storing pressure or electric energy. Therefore, at first a worst case failure mode needs to be identified choosing between those of the propulsion system or power system. If the former is present it is assumed that its worst failure mode (i. e. instantaneous release of pressure or an explosion) will produce the worst failure effects when compared to that of a power system. However, in order to assign an SN to that mode it is necessary to identify the on-board fuel type. In particular this study distinguishes between the cold gas, solid, cryogenic and hypergolic fuel. Based on their reactivity with the oxidizer, sensitivity to shock and corroding properties, it is assumed that the severity number associated with those fuels would be: 1 for modes involving cold gas and solid fuels, 2 for those involving cryogenic fuels and 3 for those involving hypergolic fuels.

If on the other hand, a propulsion system is absent or passivated, a burst of a battery pack is to be assumed as the worst failure mode of the power system and is associated with the 4th level of severity (see Table 3), i. e.with SN equal to 1.

The PNs of those failure modes are determined by using the values of Table 5, representing the probability of occurrence of an in-orbit fragmentation (due to propulsion and power systems) with respect to (w.r.t) objects age. These figures were extrapolated from the historical data regarding the in-orbit explosions available in the ESA's DISCOS database, as of June 2016. The n/a symbols in the table indicate fields that have no sense, e. g. there cannot be an ADR capture of an object launched in the period between 2000 and 2009 that is 21 years old, or of an object that was launched in the period between 1957 and 1969 that is only 1-5 years old. Of course, should a deeper analysis of the mentioned failure modes reveal a different PN, those numbers are to be considered instead (e. g. see comments of Table 8).

Using the previously defined severity and probability numbers it is possible to assign the criticality numbers by using the following formula $CN = SN \cdot PN$ or the criticality matrix represented in Table 6. With this in mind, an object is to be considered as critical for capture if:

- the consequences of the failure mode are to be considered catastrophic, i. e. the SN of the failure mode is 4, or
- the failure mode is greater or equal to 8 (see Table 6).

Table 5: Probability of on-board system failures w.r.t objects age

	Age of object [yr]					
Launch period	1-5	6-10	11-15	16-20	21-50	>50
1957-1969	n/a	n/a	n/a	n/a	$2.28 \cdot 10^{-3}$	$< 10^{-5}$
1970-1979	n/a	n/a	n/a	n/a	$< 10^{-5}$	n/a
1980-1989	n/a	n/a	n/a	n/a	$8.65 \cdot 10^{-4}$	n/a
1990-1999	n/a	n/a	n/a	$1.18 \cdot 10^{-3}$	$1.18 \cdot 10^{-3}$	n/a
2000-2009	n/a	$4.7 \cdot 10^{-3}$	$1.57 \cdot 10^{-3}$	$< 10^{-5}$	n/a	n/a
2010-2016	$6 \cdot 10^{-3}$	$< 10^{-5}$	n/a	n/a	n/a	n/a

Table 6: Criticality matrix [13]

Severity	SN	Probability			
		10^{-5}	10^{-4}	10^{-3}	10^{-1}
		PN			
		1	**2**	**3**	**4**
Catastrophic	**4**	4	8	12	16
Critical	**3**	3	6	9	12
Major	**2**	2	4	6	8
Negligible	**1**	1	2	3	4

In these cases, any close contact with the target is to be avoided by using only net-based methods that can perform the capture from a considerable stand-off distance. Moreover, a special care should be exerted during the capture and stabilization of these objects to avoid shocks and sources of sparks. Therefore, harpoon-based methods are to be avoided since they assume a penetration of a target and thus would only add more hazard to the mission.

For the remaining CNs, the associated ADR capture methods were chosen as follows:

- **robotic/tether-based** methods for CNs **1-4** or for failure modes classified as **negligible,**
- **net/contactless** methods for the CN equal to **6.**

The association was carried out based on the engineering judgment regarding the maturity of a technology and distance that the chaser spacecraft needs to maintain during the capture. Thus, it was performed only with safety in mind given the many uncertainties surrounding most of the currently considered ADR targets.

Even at this point the ambiguity in choosing between ADR methods is still present since mainly the classes of methods, instead of individual methods, have been used in the previous association. Therefore a last step of the layer is to be performed to narrow down the method or methods starting from those identified before, as it will be illustrated hereafter.

3.3.2 Levels of non-cooperativeness definition

The level of non-cooperativeness of an object defines in this study the degree of difficulty that a capture maneuver is likely to face due to the angular rate, berthing feature existence, material properties and mechanical clearance of a capturing interface of a target. Therefore, 14 levels were identified considering all the possible permutations between the mentioned characteristics as visible in Table 7. The levels are expressed as a combination of an Arabic numeral (from *1* to *7*, with *1* being the *least non-cooperative* and *7* the *most non-cooperative* level) and a letter indicating the dimensions of the mechanical clearance of the capturing interface (i. e. *large (L)* or *small (S)*) (see Fig. 1). As in the development of the taxonomic tree, not all of the permutations made sense (e. g. an an-isotropic berthing feature), which is why they were omitted from the Table 7.

The traits used to define the levels of non-cooperativeness are described as follows.

The **angular rate** (i. e. Rate in Table 7) of an object is defined as: *low*, if the angular velocity of the target is below $5\,{}^{\mathrm{deg}}\!/\!{}_{\mathrm{s}}$ (i. e. $\boldsymbol{\omega}_t \leq 5\,{}^{\mathrm{deg}}\!/\!{}_{\mathrm{s}}$), *medium*, if it is comprised between 5 and $18\,{}^{\mathrm{deg}}\!/\!{}_{\mathrm{s}}$ (i. e. $5\,{}^{\mathrm{deg}}\!/\!{}_{\mathrm{s}} < \boldsymbol{\omega}_t < 18\,{}^{\mathrm{deg}}\!/\!{}_{\mathrm{s}}$), and *high*, if it is higher then $18\,{}^{\mathrm{deg}}\!/\!{}_{\mathrm{s}}$ (i. e. $\boldsymbol{\omega}_t \geq 18\,{}^{\mathrm{deg}}\!/\!{}_{\mathrm{s}}$). The thresholds between the various rates were chosen based on: the current

Table 7: Levels of non-cooperativeness of a target

Level	Capture interface & ADR association								
	Rate			Berth.		Material		Mechanical clearance & ADR	
	Low	Med	High	Y	N	Iso	An	L	S
1	x			x		x		Manipulator	
2	x				x	x		Clamp w sync./Tether	Tether
3	x				x		x	Clamp w sync./Net	Net
4		x		x		x		Manipulator w sync.	
5		x			x	x		Clamp w sync./Tether	Tether
6		x			x		x	Clamp w sync./Net	Net
7			x					Contactless	

capabilities of robotic manipulators to capture a tumbling target without relative attitude synchronization (i. e. $\boldsymbol{\omega}_t \leq 5\,\mathrm{deg/s}$) [14, 15] and a value of the angular rate above which any synchronization effort would be considered very difficult (i. e. $\boldsymbol{\omega}_t \geq 18\,\mathrm{deg/s}$) [16].

Therefore, the most non-cooperative level was identified only by the angular rate of an object and associated with contactless "capture" method given that any synchronization effort at this level would be very difficult [16] and thus a direct contact with the target was considered as extremely difficult and thus discarded.

The **berthing feature existence** (i. e. Berth. in Table 7) is defined as *true (Y)* if there there is a dedicated berthing feature on a target (e. g. a launcher adapter ring (LAR) common on many spacecrafts). Otherwise, a *false* value *(N)* is associated with this trait since in this case the capture is to be performed on a surface of the object. An existence of a berthing feature is to be considered as advantageous for the capture since manipulator-based methods could be used in these cases and are therefore associated with levels having that trait. In case of existence of multiple berthing features on the object, the trait is defined as true and the most advantageous one (from the mission point of view) is taken into consideration for further classification.

The **material** of the capturing interface reflects the versatility and reliability of the capture method and is distinguished as *isotropic (Iso)* (e. g. metal, ceramics or polymer) or *an-isotropic (An)*. The latter is more suitable for distributed load applications during the capture (such as occurring during the usage of clamp/net-based methods) while the former is expected to also withstand concentrated loads (such as occurring during the usage of manipulator/harpoon-based methods).

The **mechanical clearance** of the capturing interface reflects the overall complexity of the approach and capture operations. It is defined in this study as a surface of a circle centered on the capturing interface and it is considered as *small (S)*, if it is smaller then $0.28\,\mathrm{m}^2$, and *large (L)*, if it is equal or larger then that. The threshold value was calculated considering the ESA's recommendations regarding mechanical clearance of mechanisms [17] and the lowest value of the typical performance to be achieved by a GNC system in $x-, y-, z-$position during a berthing (i. e. $0.1\,\mathrm{m}$) [18].

A low value of the mechanical clearance of the capture interface is to be considered a limiting factor in the ADR association excluding the usage of clamp/tentacles-based methods while promoting the usage of manipulator/tether-based methods.

The ADR association visible in Table 7 was done using a qualitative approach based on the engineering judgment of the capabilities of the considered ADR methods. Therefore, a manipulator was considered as the first choice in case of an object having a dedicated berthing feature since it is the most mature one among the considered capture technologies. A non-existing berthing feature precludes the usage of the manipulator thus, it was assumed that these cases should be tackled by methods capable of capturing a surface rather then a particular feature. Hence, clamp and tethered methods were considered in these cases, based on the mechanical clearance available on the target.

Please note that this association is only to be used as a complement to the one already performed with the break-up risk analysis and as an additional filter to identify the most suited capture ADR method w.r.t. the overall safety of a mission.

For example, if the CN of an object dictates that the associated capture methods are robotic/tether-based and its level of non-cooperativeness is equal to 1L, the most suited capture method for that target would be a manipulator-based method due to its level of non-cooperativeness.

Should there ever arise a conflict between the associated capture methods identified during the break-up risk analysis and definition of the levels of non-cooperativeness of an object, the most suited method or methods identified with the former analysis are always to have the priority.

For example, should the identified ADR class be net-based, due to a high CN, and the level of non-cooperativeness equal to 1L, a net-based system is to be considered as the most suitable to capture method for that object, instead of the manipulator-based system as indicated in Table 7, due to the high criticality number of the possible failure mode.

4. Application results

The application of the developed taxonomy is illustrated hereafter using as targets representative objects of the most attractive families of space debris for future ADR missions, such as the European Envisat, Soviet/Russian SL-16, SL-8, SL-3 rocket bodies and Soviet/Russian Meteor satellites [2, 19]. The results are visible in Table 8 and 9.

Most of the physical data about the objects was obtained from the ESA's DISCOS database. However, other traits were obtained from on-line resources such as: Encyclopedia Astronautica[††], Gunter's Space Page[‡‡], Earth Observation Portal[§§] and RussianSpaceWeb.com[¶¶]. Others, evidenced in tables with an asterisk (*), were defined based on the engineering judgment using the available resources (e. g. assuming that old objects are subject to a regular slow rotation around one axis was based on the conclusions of [20] and not actual data). In fact, currently there are no publicly available databases[***] that contain these kind of information. We acknowledge that this might undermine the precision of the identified ADR capture methods for the use-case objects. However, we are convinced that this does not undermine the validity of the developed taxonomy and its main characteristic to concisely describe the main properties of objects and the hazard that they represents for an ADR effort. Therefore, the results of these applications are to be considered at the moment only as indicative. Moreover, please note that the probability number of the Envisat has been added based on the results of the e.Deorbit CDF Study Report [21].

From these examples it is possible to make a conclusion that objects having a hypergolic type of fuel on-board are most likely to be tackled by net-based methods, due to their high criticality number. However, this does not hold true if those targets were launched in the time frames having the on-board system failure probability $\leq 10^{-4}$ (see Table 5), as it can be seen in Table 9, where a similar Cosmos-3M rocket body was used as in Table 8, but the result of the ADR association was completely different.

For targets having a non-hypergolic type of fuel on-board the most suited ADR capture method depends greatly on the identification of their levels of non-cooperativeness. Which in turn dictate that if we are to peruse the ADR in the near future the traits identified in the Table 7 will need to be identified for the most appealing ADR targets.

5. Conclusions

A method for the classification of space debris and ADR association has been described. The outcome of the taxonomy is an easy to interpret acronym, which describes at a glance the most prominent features of objects and the hazard they pose to an ADR effort. The method has been formulated in two layers, where at first the taxonomic tree of space debris is developed and objects grouped into main classes. From there objects are filtered and only those that are practical for ADR are considered in the next layer. In the second layer a break-up risk index and levels of non-cooperativeness of objects are assigned to individual objects, therefore narrowing down the ADR association and making it possible to individuate the best method or methods for individual objects. The application of the method to representative objects of the most attractive families of space debris for future ADR missions has been also illustrated. The results of that application indicate that objects having a hypergolic type of fuel (e. g. Soviet/Russian SL-8 rocket bodies) are most likely to be tackled by net-based methods due to their high criticality num-

[††]URL: http://goo.gl/iVOgvS
[‡‡]URL: http://goo.gl/f21ATh
[§§]URL: https://goo.gl/SWwGSl
[¶¶]URL: http://goo.gl/XR6JK
[***]At least to best of our knowledge.

Table 8: Examples of taxonomy application

DISCOS Name	**Envisat**	**Zenit-2 II stage**	**Cosmos-3M II stage**
COSPARID	2002-009A	1985-097B	1967-045B
Mass [kg]	8110	8225.970	1434
DISCOS classification	Payload	Rocket Body	Rocket Body
Shape	Box + 1 panel	Cylinder	Cylinder
Mean size [m]	13.5	7.15	3.3
Mean area [m^2]	74.39	33.426	10.179
Orbital state	Uncontrolled	Uncontrolled	Uncontrolled
Attitude state	Tumbling	Reg. rotating*	Reg. rotating*
External shape	Reg. polyhedral	Reg. convex	Reg. convex
Size	Large	Large	Large
AMR	Low	Low	Low
Debris class	UTPLlo	URXLlo	URXLlo
Severity number	3	2	3
Probability number	1	2	3
Risk index	3	4	9
Angular rate	Low	Low*	Low*
Berthing feature	Yes	No*	Yes*
Interface material	Isotropic	Isotropic*	Isotropic*
Mech. clearance	Small	Large*	Large*
Non-coop. level	1S	2L	1L
Taxonomic acronym	URPLlo-3-1S	URXLlo-4-2L	URXLlo-9-1L
ADR capture methods	Manipulator-based	Clamp w sync./Tether-based	Net-based

Table 9: Examples of taxonomy application

DISCOS Name	**Cosmos-3M II stage**	**Meteor 2-8**	**Vostok stage 3**
COSPARID	1973-042B	1982-025A	1970-047B
Mass [kg]	1434	1500	1427.16
DISCOS classification	Rocket Body	Payload	Rocket Body
Shape	Cylinder	Cyl.+ 2 Pan	Cylinder
Mean size [m]	3.3	2.95	3.2
Mean area [m^2]	10.179	5.718	10.414
Orbital state	Uncontrolled	Uncontrolled	Uncontrolled
Attitude state	Reg. rotating*	Reg. rotating*	Reg. rotating*
External shape	Reg. convex	Reg. convex	Reg. convex
Size	Large	Large	Large
AMR	Low	Low	Low
Debris class	URXLlo	URXLlo	URXLlo
Severity number	3	3*	2
Probability number	1	2	1
Risk index	3	6	2
Angular rate	Low*	Low*	Low*
Berthing feature	Yes*	No*	No*
Interface material	Isotropic*	Isotropic*	Isotropic*
Mech. clearance	Large*	Large*	Large*
Non-coop. level	1L	2L	2L
Taxonomic acronym	URXLlo-3-1L	URXLlo-6-2L	URXLlo-2-2L
ADR capture methods	Manipulator-based	Net-based	Clamp w sync./Tether-based

ber. However, this outcome depends greatly on the age of the target and its year of launch, since some of the objects have a very small probability of in-orbit failure. For all the other targets, the most suited ADR capture method depends greatly on the identification of their levels of non-cooperativeness which requires a more detailed definition of their physical and dynamic properties, currently unavailable to the general public. Thus, if we are to to peruse the ADR in the near future the traits identified in this method as critical in classifying the objects need to be identified at least for the most appealing ADR targets. Moreover, the probability of on-board system failures needs to be refined to include the cumulative risk of fragmentation of objects that would permit grainier changes of the probability according to ADR missions duration, which is why it represents the future work of this study that will further improve the developed taxonomic method.

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