Taxonomy of LEO space debris population for ADR capture methods selection

Marko Jankovic and Frank Kirchner

Abstract This paper illustrates a novel taxonomy method for LEO space debris population whose aim is to classify the LEO space debris objects such that it is possible to identify, safety wise, for each one the most suitable Active Debris Removal (ADR) capture method. The method is formulated in two distinct layers. In the first layer, a main class of an object is identified, based on its most prominent dynamical and physical traits. At this stage identifying the most suited ADR method is still a difficult task, due to the crude nature of the parameters used for the classification. The second taxonomic layer is thus performed on top of the first one. In it the break-up risk index and levels of non-cooperativeness of an object are identified and the ADR association is refined. Examples of application of the developed taxonomy are presented at the end of the paper 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.

Key words: Space debris, active debris removal, taxonomy, taxonomic tree, leo, levels of non-cooperativeness, break-up risk index.

1 Introduction

With the start of the human space activities in 1957, the LEO, once pristine and void, started showing signs of congestion which will lead to a critical density of objects in orbit and eventually to a cascading problem predicted by Kessler and Cour-Palais

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in 1978, called the Kessler syndrome. The space community is trying, up-to-date, to counteract this syndrome only with a set of non-binding mitigation measures that would, if applied correctly, assure no future sources of space debris [8]. Despite these efforts, studies on the subject showed that 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, despite tthose measures [9]. Thus, to stabilize the LEO environment and reduce the population of space debris the in-orbit mass needs to be actively removed [8].

Among all the phases of an ADR mission, the capture appears to be the most challenging one, since it generally involves close-range maneuvering and contact with a target. Moreover, no spacecraft has ever performed a capture of a completely non-cooperative target. Furthermore, 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 and difficult phase of an ADR mission.

Targets considered as relevant in this study are those larger then 10 cm, since they are considered as lethal for any active satellite and are capable of generating more lethal fragments when impacting an operation spacecraft [11, 6]. Moreover any removal of objects smaller or equal to 10 cm is as of today considered non practical [6, 7]. With this in mind, the number of suitable ADR technologies to tackle those targets can be restricted and essentially divided into two categories: *contact* and *contactless* [4].

The *contact* methods considered in this paper include technologies based on: robotics (e. g. clamps, manipulators) and tethers (e. g. nets, harpoons). The *contactless* methods considered in this paper include technologies based on: plume impingement (e. g. chemical, electrical thrusters), ablation (e. g. lasers, solar concentrators) and electromagnetic forces (e. g. eddy brakes, electrostatic tractors).

They all have advantages and disadvantages but none of them can be applied to every type of target. Therefore, choosing one ADR method over another, in the initial stages of the mission planning, is essential. Nevertheless, this is generally a difficult and time consuming task, especially in the initial stages of the mission planning, 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.

One way of solving the first part of the problem would be to provide a means to compare the listed capture devices. This was attempted by creating a survey where experts in the field of ADR were able to evaluate (to best of their knowledge) ADR technologies in few categories, such as: technological availability, safety, reusability, versatility, etc. The total number of experts that agreed to participate to the developed survey was 35. Their professional status ranges from university professors and senior researchers in leading European and American academic research institutions to project managers in leading European aerospace companies.

The result of the survey concerning the capture technologies can be seen in Fig. 1. A higher bar represents a better overall weighted score of a method and different color of a bar indicates the weighted score of each category. For the scores, median values of the answers were used in order to take into consideration the overall distribution of the answers since not all of the technologies were evaluated by the same number of experts.

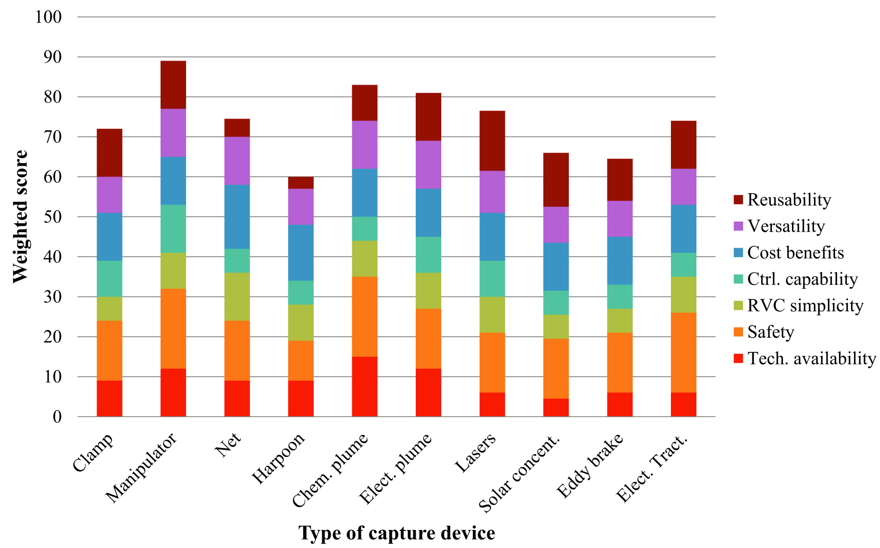

Fig. 1 Capture devices classification based on answers from 35 experts

Analyzing more closely Fig. 1, it is evident that manipulator-based capture technique has the highest score, as it was expected, since it is the most mature technology among them all. However, the scores of other technologies are not that different, evidencing once again the difficulty in raking them and consequently choosing one method over another. This is especially true if other factors need to be taken into consideration and not only the overall score, e. g. bigger safety requirements, versatility, etc. Therefore, another way is needed to solve more readily the mentioned problem. In this paper, this has been identified as providing a proper scientific classification of the space debris population that is able to point out the most suitable ADR method safety wise via a taxonomic method. 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 [2], 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 [4].

The structure of the remainder of the paper is as follows: Sect. 2 is dedicated to a brief review of previous studies of taxonomy of space debris. Sect. 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 to an ADR effort. Sect. 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. Sect. 5 provides the concluding remarks of the paper and the envisioned future work that will improve the developed method.

2 State-of-the-Art

In case of space debris, the ancestral decent of an object is generally known in advance which is why the taxonomy of space debris is done in reveres with respect to a biological taxonomy [2]. Despite this advantage, the taxonomy of space debris is still an unexplored field of research due to the large dimensions of the parameter space and immaturity of almost all ADR technologies. Nevertheless, there have been in the past some attempts to develop a taxonomy of space debris objects and the most relevant ones are outlined in what follows.

Wilkins, M. P. et al. in [14] 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 [14]. 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 [4].

Früh, C. et al. in [2], 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) [4].

3 Method Formulation

The taxonomy described in this paper consists of two layers developed to aid the initial mission planning of future ADR missions and provide an easy way to visualize, with an acronym (see Fig. 2), the main characteristics of an object and its hazard. The first part of the acronym, defined in Fig. 2 with a label "*Debris class*", refers to the first layer of taxonomy and it indicates the class of a debris based on its most prominent physical and dynamical characteristics. 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 for that class can be made. However, an uncertain result is to be expected due to the crude nature of the traits used for the formulation of the classes [4].

To eliminate the mentioned uncertainty and narrow down the ADR association, a second layer of taxonomy is to be performed, on per object basis, and is indicated in Fig. 2 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 [4].

$$\underbrace{\underbrace{\text{URXLlo}}_{\text{Debris class}}\text{-}\underbrace{\text{9-1L}}_{\text{Debris hazard}}}$$

Most suited ADR method: Net-based

Fig. 2 Example of application of the taxonomic method 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 7 for more details) [4].

3.1 Debris Classes

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 [10]. 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 [2]. 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 [4].

The principle of taxonomic distinction dictates that placing an objects into a taxa must be performed without ambiguity [2]. 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 in this layer are: the orbital state, attitude state, shape, size and area-to-mass ratio (AMR). The definition of those characteristics can be seen in Table 1. A more detailed description of the listed characteristics can be found in our previous publication on the topic [4].

Table 1 Main characteristics of the first layer of taxonomy [4]

Characteristics	Definitions
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): $> 2\,\mathrm{m^2/kg}$

Using the previously defined characteristics it is possible to build a taxonomic tree of space debris objects (see [4]) which allows us to identify the LEO classes of space debris objects. The result of this step are 18 classes, out of which only four (see Table 2) are considered as relevant for any future ADR effort, given their mass and size. Therefore, only those classes were considered for the next taxonomic layer.

Table 2 Main classes of the taxonomic tree

Acronym of the class	Example object
Passively stable, intact objects	
URXLlo	Upper stages/decommissioned spacecrafts with momentum bias
URPLlo	Decommissioned spacecrafts with momentum bias
Intact uncontrolled objects	
UTPLlo	Generic decommissioned tumbling spacecrafts
UTXLlo	Tumbling upper stages

3.2 Debris Hazard

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 its capture in order to pin-point the most suited ADR capture method for that object, safety wise. This requires a more specific knowledge of physical and dynamical traits of objects, not all of which are available in publicly accessible databases. Therefore, 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 yield a more precise results [4].

The break-up risk index of an object is defined as the highest criticality number (CN) calculated, in accordance with the ESA's standard on Failure modes, effects (and criticality) analysis (FMEA/FMECA) (see [1]), as a product between the severity number (SN) and probability number (PN) of possible failure modes of space debris objects [4].

According to [1], the FMEA shall be performed mainly by: (a) describing the product to be analyzed, (b) identifying all potential failure modes and their effects on the product, (c) evaluating each failure mode in terms of the worst potential consequences and assigning a severity category, (d) identifying preventing measures for each failure mode and (e) documenting the analysis. Based on this methodology and data from the ESA's Database and Information System Characterising Objects in

Space (DISCOS[1]) it was possible to identify (for large LEO non-passivated objects) two types of possible failure modes of which we have documented information: explosions or malfunctions of propulsion/attitude systems and explosions of battery packs. The distribution of those two events varies between spacecrafts and rocket bodies and is 33 and zero events due to propulsion and batteries, respectively, in case of rocket bodies while it is 3 and 10 events due to propulsion and batteries, respectively, in case of spacecrafts. Collisions are excluded from this study since a only a total of 6 events occurred versus 46 due to a malfunction of on-board systems. Future studies might overcome this current limitation of the method.

For passivated objects, no break-up risk exists from on-board stored energy, however the embrittlement of external surfaces due to the thermal cycling and erosion is to be expected and is considered in this study as a possible failure mode.

The estimated consequences of each identified failure mode and thus the associated SN of each mode are the following. For explosions or malfunctions of propulsion/attitude systems the severity of that failure mode depends greatly on the stored fuel type. This study distinguishes between the cold gas, solid, cryogenic and hypergolic fuel. Based on the median number of fragments generated from 44 LEO explosions, it is assumed that the severity number associated with those fuels is equal to: 1 for modes involving cold gas, 2 for those involving cryogenic and solid fuels and 3 for those involving hypergolic fuels. SN 4 is reserved for objects having hypergolic type of fuel in large quantities and liquid form. This situation is typically to be expected in case of objects that have been decommissioned early in the mission due to an irrecoverable in-orbit failure or wrong orbital insertion.

For explosions of battery packs an SN of 2 was assumed due to a median number of generated debris from historical data (i. e. 65.5 fragments).

In case of ruptures of external surfaces, due to the embrittlement, the assumed SN is equal to 1, which corresponds to a minor or negligible mission degradation mainly due to the cracking of the external paint.

The next step towards the definition of the break-up risk index is the identification of the probability of occurrence of assumed failure modes. This was done by using the probability of occurrence levels visible in Table 3 and the data, extrapolated from the ESA's DISCOS and US Air Force's Space Track[2] databases.

Table 3 Probability levels, limits and numbers

Level	Probability 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	$P \leq 10^{-5}$	1

[1] URL:https://goo.gl/e279ln

[2] URL: https://www.space-track.org

A distinction was made between payloads/spacecrafts and rocket bodies since a significant difference in the number and distribution of break-up events between these two types of objects (see Fig. 3) was determined. Moreover, for non-passivated objects the non-parametric Kaplan-Meier estimator was used to determine their cumulative failure probability instead of the probability calculated as a normalization of the number of events with respect to the number of launches, as done in our first paper on this topic [4]. The mentioned estimator was originally developed in medicine to estimate a survival curve from a population sample, including incomplete observations [5], which is exactly the case of space debris since the estimation of the cumulative failure probability needs to take into consideration re-entered objects.

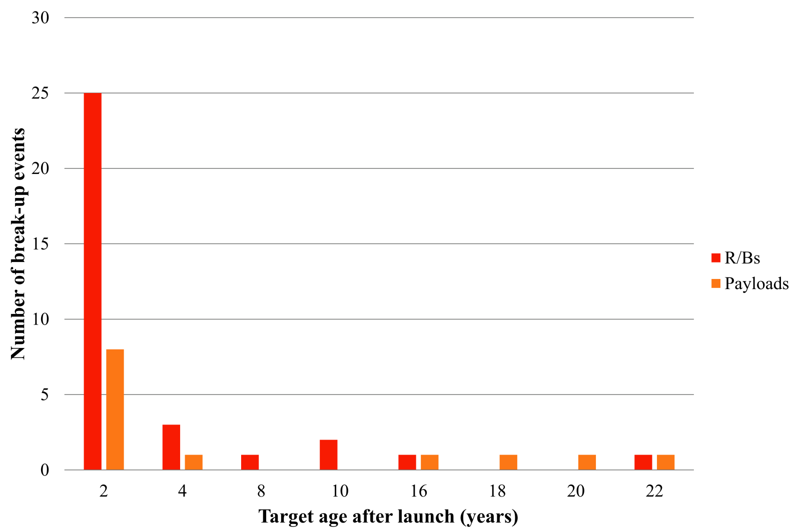

Fig. 3 Distribution of LEO break-up events (source: DISCOS database)

Due to a vary small number of samples (i. e. 46) the calculation of a cumulative probability distribution was made without any distinction between the failure modes. A future study might tackle this point in more depth and overcome this current limitation of the method. In total, a population of 2304 and 2442 large, defunct, LEO spacecrafts and rocket bodies, respectively, was analyzed using the data from the US Air Force's Space Track and ESA's DISCOS databases. The result of the analysis are the cumulative failure probability distributions visible in Figs. 4 and 5, for spacecrafts and rocket bodies, respectively, which can be used to obtain PNs of desired non-passivated objects if the data is paired with Table 3.

For passivated objects the PN, is determined by calculating the following linear functions, $PN = 2 \times 10^{-4} \times \text{age}$, for spacecrafts, and $PN = 4 \times 10^{-4} \times \text{age}$, for rocket bodies, to reflect the maximum values of PNs obtained with the Kaplan-Meier estimations (see Figs. 4 and 5).

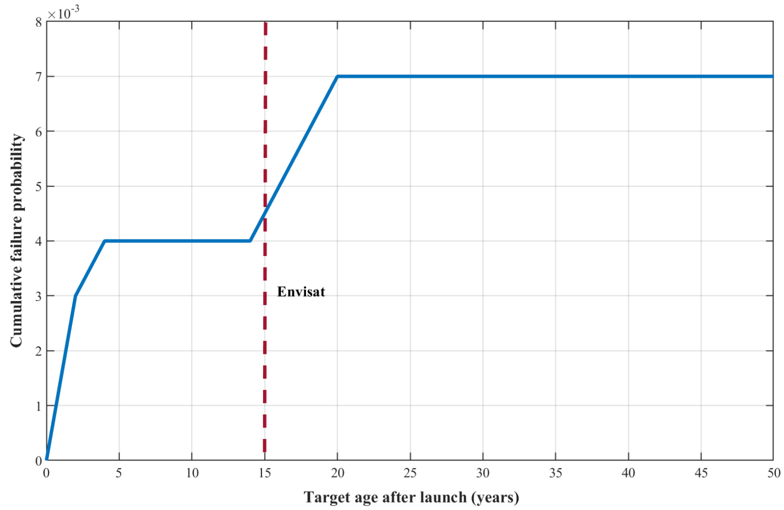

Fig. 4 Cumulative failure probability distribution for spacecrafts with Envisat as an example object

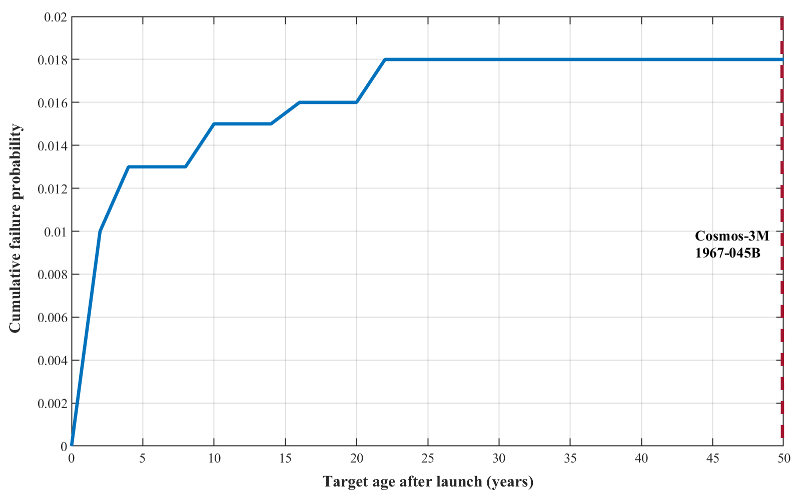

Fig. 5 Cumulative failure probability distribution for rocket bodies with Cosmos-3M 1967-045B as an example object

Using the previously defined severity and probability numbers it is possible to assign the criticality numbers to each failure mode of each object by either using the formula: $CN = SN \cdot PN$ or the criticality matrix represented in Table 4.

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 (see Table 4), or
- the failure mode is greater or equal to **8** (see Table 4).

Table 4 Criticality matrix

Severity	SN	Probability			
		10^{-5}	10^{-3}	10^{-1}	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 a capture from a considerable stand-off distance. Moreover, a special care should be exerted during the capture and stabilization of these objects to avoid 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.

With the identification of the break-up risk index it is possible to estimate how dangerous the capture of a specific target would be but at this stage there is no indication on how difficult it would be. Moreover, even at this point of the method the uncertainty in choosing the best ADR capture methods is still to be expected. To solve this, a level of non-cooperativeness of an object needs to be identified and is performed using Table 5. In total, 14 levels of non-cooperativeness were identified and each level is 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

Table 5 Levels of non-cooperativeness of a target [4]

Level	Rate			Capture interface & ADR association					
				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	

indicating the dimensions of the mechanical clearance of the capturing interface (i. e. *large (L)* or *small (S)*) (see Fig. 2 on page 5) [4].

The definition of the traits used to define the levels of non-cooperativeness can be seen in Table 6. A more detailed description and definition of the listed characteristics can be found in our previous publication on the topic (i. e. [4]).

Table 6 Main characteristics/taxa of the first layer of taxonomy

Characteristics	Definitions
Angular rate	Low: $< 5\,{}^{\mathrm{deg}}/_{\mathrm{s}}$ Medium (Med): $5 - 18\,{}^{\mathrm{deg}}/_{\mathrm{s}}$ High: $\geq 18\,{}^{\mathrm{deg}}/_{\mathrm{s}}$
Berthing feature existence	True (Y): *dedicated berthing feature exists* False (N): *dedicated berthing feature does not exist*
Capturing interface material	Isotropic (Iso): *e. g. metal, ceramics or polymer* An-isotropic (An): *other*
Mechanical clearance	Small (S): $< 0.28\,\mathrm{m}^2$ Large (L): $\geq 0.28\,\mathrm{m}^2$

The ADR association performed in Table 5 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 of a target. Hence, clamp and tethered methods were considered in these cases, based on the mechanical clearance available on the target. However, 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 with respect to (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, due to the high criticality number of the possible failure mode [4].

4 Method Application

To study the practicality of the developed taxonomic method, it was applied to representative objects of the most attractive families of space debris for future ADR missions, such as the European Envisat, Soviet/Russian SL-16 and SL-8 rocket bodies [8, 13]. The results are visible in Table 7.

Table 7 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	3	3
Risk index	3	6	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-6-2L	URXLlo-9-1L
ADR capture methods	Manipulator-based	Net-based	Net-based

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[3], Gunter's Space Page[4], Earth Observation Portal[5] and RussianSpaceWeb.com[6]. Others, evidenced in table with an asterisk (*), were defined based on the engineering judgment using available resources (e. g. assuming that old objects are subject to a regular slow rotation around one axis was based on the conclusions of [12] and not actual data). In fact, currently there are no publicly available databases[7] 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 taxonomic method 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 [3]. Should have we estimated its PN using Fig. 4, that number would have been different (i. e. 3 instead of 1). Therefore, the recommended capture methods would have been different, i. e. they would have been based on net/contactless technologies. This is to indicate a conservative nature of the developed method and break-up probability numbers. However, anytime that a deeper study on the cumulative probability of a break-up of an object has been performed it is advisable to be used in the developed taxonomy to obtain a more precise association.

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. 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 6 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 identifying a debris class and its capture hazard. For the latter a statistical analysis has been performed on the available data using the Kaplan-Meier estimator to estimate the cumulative probability distribution of failure modes. The application of the method

[3] URL: http://goo.gl/iVOgvS

[4] URL: http://goo.gl/f21ATh

[5] URL: https://goo.gl/SWwGSl

[6] URL: http://goo.gl/XR6JK

[7] At least to best of our knowledge.

to representative objects of three families of space debris 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 break-up risk index. For all the other targets, the most suited ADR capture method depends greatly on the identification of their levels of non-cooperativeness which was performed in this study based on the engineering judgment using limited resources. Therefore, the results are to be considered at the moment only as indicative, at least until the necessary data is made available to the public. Nevertheless, this does not undermine the validity of the developed method and its immediacy when it comes to identifying the most suited ADR capture method necessary in the initial phases of mission planning.

However, the method does not include collisions as possible source of break-up and the cumulative probability distribution is calculated using the data of both propulsion/attitude and battery failure modes, without distinction. Furthermore, only a non-parametric analysis of the probability is implemented making any future predictions of PNs impossible. Therefore, these three issues are the shortcomings of the presented method and will be tackled in our future research.

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