Progress in Aerospace Sciences 80 (2016) 18–32

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

Review and comparison of active space debris capturing and removal methods

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A R T I C L E I N F O

Article history:
Received 1 May 2015
Received in revised form
9 November 2015
Accepted 11 November 2015
Available online 20 November 2015

Keywords:
Space debris
Capturing and removal
Non-cooperativeness

A B S T R A C T

Space debris is considered as a serious problem for operational space missions. Many enabling space debris capturing and removal methods have been proposed in the past decade and several methods have been tested on ground and/or in parabolic flight experiments. However, not a single space debris has been removed yet. A space debris object is usually non-cooperative and thus different with targets of on-orbit servicing missions. Thus, capturing and removal of space debris is significantly more challenging. One of the greatest challenges is how to reliably capture and remove a non-cooperative target avoiding to generate even more space debris. To motivate this research area and facilitate the development of active space debris removal, this paper provides review and comparison of the existing technologies on active space debris capturing and removal. It also reviews research areas worth investigating under each capturing and removal method. Frameworks of methods for capturing and removing space debris are developed. The advantages and drawbacks of the most relevant capturing and removal methods are addressed as well. In addition, examples and existing projects related to these methods are discussed.

Contents

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http://dx.doi.org/10.1016/j.paerosci.2015.11.001
0376-0421/

1. Introduction

The Earth orbit is in a serious predicament caused by millions of space debris. Operational satellite vital for mankind infrastructure are threatened to be destroyed by space debris. The Kessler Syndrome states that more and more debris might be produced due to the continuous collision even if all launches into space would be stopped immediately [1]. Thus, active debris removal is of great relevance. In this context, all space companies and organizations are suggested to follow the 25-year safety standard which means a satellite should either lower its orbit and re-enter, or raise itself to a graveyard orbit within 25 years after the mission ends [2]. Since this rule is not enforced up to now, 5–10 space debris objects still need to be removed each year to stabilize the space environment according to a prediction model from NASA [3].

Space debris can be produced in different ways, such as hypervelocity impact with spacecraft wall, high-intensity explosion or low-intensity explosion, dysfunctional satellites and rocket upper stages. As early as 1975, NASA has already investigated the mass distribution of space debris and performed several experiments on ground. Power and exponential function models are applied to estimate the mass distribution of the space debris [4]. Till 2013, the mass of space debris in space is over 3 million kilograms and there is no sign of slowing down [5]. By the day of January 8, 2015, the number of space objects with sizes larger than 10 cm is beyond 17,000, with 77% of them being space debris (Table 1).

Spatial and mass distributions of the space debris have been introduced by Liou, from whose point of view, in Low Earth Orbit (LEO), the altitude close to 800 km is the most crowded orbit, and altitudes close to 600 km, 800 km, and 1000 km are the massiest orbit since most of space debris with mass over 50 kg are located in those regions [6]. The debris objects in inclination region of 82.5–83.5° and altitudes between 900 km and 1050 km are considered as typical Active Debris Removal (ADR) targets. Bonnal also indicated that space debris whose inclination ranging from 82.83 to 82.991°, and altitudes close to 1000 km should be a given priority [7]. A list of 22 most critical ADR targets has been presented by Wiedemann [8], with Envisat being the most threatening target. Other threatening debris are often rocket upper stages from Zenith-2. The Zenith-2 upper stage is cylindrical with a diameter of 3.9 m, a length of 10.4 m and a mass of 8226 kg. Since five of them are at a similar inclination, similar Right Ascension of the Ascending Node (RAAN) and similar altitude, they could be removed by a single ADR mission with several kits to save cost [9]. Among these threatening targets, most of them are tumbling due to their residual angular momentum. Therefore, research on how to treat these tumbling targets is crucial as well.

Table 1
Orbital population till January 8, 2015 [127].

Status	Operational satellite	Debris	Total
On orbit	3994	13,131	17,125
Decayed	3049	20,192	23,241
Total	7043	33,323	40,366

To motivate this research area and facilitate the development of space debris removal, this paper provides the existing active space debris capturing and removal methods and associated research areas. It is organized as follows: in Section 2, framework of methods for capturing space debris is developed. Advantages and drawbacks of the most relevant capturing methods are addressed. Examples and existing techniques related to these methods are introduced in detail. Section 3 presents various space debris removal methods and their advantages and drawbacks. The state-of-the-art related to each removal method is discussed. It also provides some worldwide removal projects. In Section 4, space debris objects are categorized into four groups by their non-cooperativeness and examples under each category are provided. To facilitate decision-making through these existing capturing and removal methods, Section 4 provides tailored associated capturing and removal methods for each category. Finally, a conclusion is drawn in Section 5.

2. Capturing methods

A space mission for active space debris capturing and removal consists of the following phases: Launch and Early Orbit Phase (LEOP), far-range rendezvous phase, close-range rendezvous phase, capturing phase and removal phase. These phases can be performed either autonomously or remotely controlled by ground-based mission operations. Capturing phase plays a crucial role in the entire mission process. Conceptually, many methods for space debris capturing have been proposed. According to their characteristics, the methods are divided into two main categories: contact and contactless capturing methods. Since contactless capturing methods, e.g., Electrostatic Tractor [10] and Gravity Tractor [11], which use the electrostatic forces or gravitation, are primarily considered for asteroid orbit deflection, they are not further discussed here. Fig. 1 displays a framework of existing capturing methods.

Advantages and drawbacks exist in any of those options, and there is not a single capturing method, which can deal with all kinds of space debris. Table 2 lists the most relevant and investigated capturing techniques for space debris removal missions and also their advantages and drawbacks. A comparison is drawn in this table. Detailed information about each technique and related researches are provided sequentially.

2.1. Stiff connection capturing

2.1.1. Tentacles capturing

In ESAs e.Deorbit project, capturing using tentacles, can be performed either with or without a robotic arm. With a robotic arm used, tentacle capturing embraces the space debris with a clamping mechanism after holding a point on the target by the robotic arm. Finally, a velocity increment by the chaser will deorbit the combined object [12]. A trade off shows that tentacle capturing with a robotic arm leads to a higher cost, mass, volume, hazardousness and complexity of design compared to the one without a robotic arm [13]. The simulation of the target grabbing without a robotic arm has been performed successfully, but the GNC requirements are more stringent due to high precision

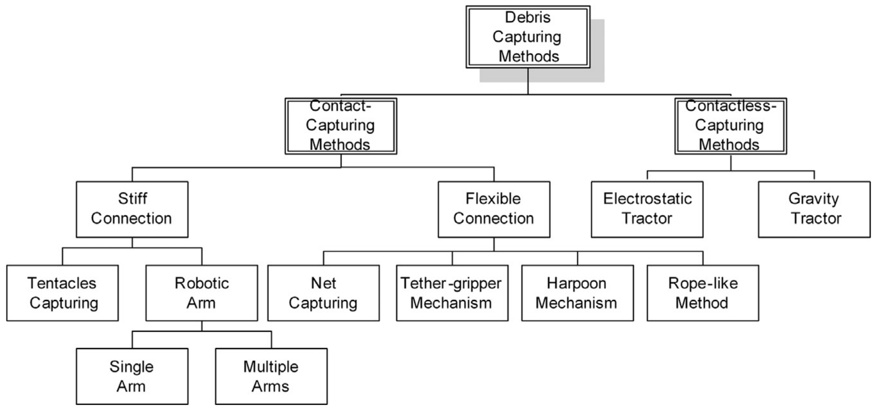

Fig. 1. Concept diagram of capturing methods.

requirements. Tentacle capturing without a robotic arm follows the capturing before touching strategy, i.e., the tentacles should ideally embrace the target before performing physical contact. In this way, the bouncing of the chaser satellite is avoided and the attitude control system is allowed to stand by during capturing. The clamping mechanism is then locked and the composite (chaser and target) essentially turns stiff after capturing [14].

Aviospace is working on the project CADET which performs space debris capturing using tentacles. The tentacles are in a closed configuration made by belts to soften the contact between tentacles and target. The material of the belts can e.g., be Zylon+VITON or PES. Finite element models have been established to simulate the capturing process and assess the dynamic behavior during the chaser-target mating process. Several ground-based test concepts have been proposed, and the detailed design has been in progress since June 2014 [15].

Another type of tentacles is inspired by biology, i.e., linked to the morphology and function alike of the snake, elephant trunks or octopus arm. Two examples are provided in this paper. Yoshida and Nakanishi have proposed a concept of Target Collaborativize (TAKO) Flyer which contains a main service satellite and a TAKO Gripper. Since most of non-operational satellites are tumbling and failed to provide information to the chaser satellite, the TAKO Flyer is designed for collabrativizing the target by capturing the target and stabilizing its tumbling motion through several thrusters operation installed on the TAKO Gripper. The grapple fixtures and optical markers on the TAKO Gripper make the target cooperative to the main chaser satellite. The TAKO Gripper is composed of several fingers driven by the gas pressure in the pneumatic bellows. However, the performance of this concept still needs to be verified [16]. McMahan has designed a continuum manipulator OctArm. OctArm version V contains three sections connected by the endplates. Each section is constructed with air muscle actuators, and it is capable of two axis bending and extension with nine degrees of freedom [17]. The dynamic model of the flexible tentacles can be derived from Langranges equations. The energy terms are obtained by the shape function based principles [18]. Four types of tentacles capturing methods are displayed in Fig. 2.

2.1.2. Single arm capturing

Robotic arm technology has been applied in many on-orbit servicing missions, such as ETS-7 of JAXA [19], Canadarm2 [20],

Table 2
Overview of relevant capturing techniques.

Capturing methods	Advantages	Drawbacks	Examples	Institute/Sources	Reference
Tentacles	1.Stiff composite;	1.Complicated rendezvous phase;	e.Deorbit	ESA	[12]
	2.Easy to test on ground;	2.Possible to be bounced;	CADET	Aviospace	[15]
	3.Higher Technology Readiness Level(TRL)	3.Accurate relative positioning and velocity needed.	TAKO	Japan	[16]
			OctArm	USA	[17]
Single robotic arm	1.Stiff composite	1.Higher probability of collision;	DEOS	DLR	[23]
	2.Easy to test on ground;	2.Grappling point required;	EPOS	DLR	[25]
	3.Higher TRL	3.Rendezvous and docking needed.	FREND	DARPA	[27]
Multiple arms	1.Stiff composite	1.Complex control system;			
	2.Easy to test on ground;	2.Higher mass and cost;	ATLAS	UK	[40]
	3.Flexible capturing	3.Rendezvous needed.			
Net capturing	1.Allows a large capturing distance;	1.Hard to control;	ROGER	ESA	[51]
	2.Reduced requirements on precision;	2.Risk of critical oscillations;	e.Deorbit	ESA	[12]
	3.Compatible for different size of debris.	3.Hard to test on ground.	D-CoNe	Italy	[54]
			REDCROC	Colorado	[55]
Tether gripper	1.Allows a large capturing distance;	1.Difficult to test on ground;	ROGER	ESA	[51]
	2.Short capture operation time;	2.Grappling point required;			
	3.Lower mass and cost.	3.Lower reliability.	TSR	China	[72]
	1.No grappling point required;	1.Risk of generating fragments;	GS	Astrium	[85]
Harpoon	2.Allows a stand-off distance to target;	2.Risk of breakup			
	3.Compatible with different target types (rocket body or satellite).	3.Flexible connection, difficult to predict the movement of a target.	e.Deorbit	ESA	[52]

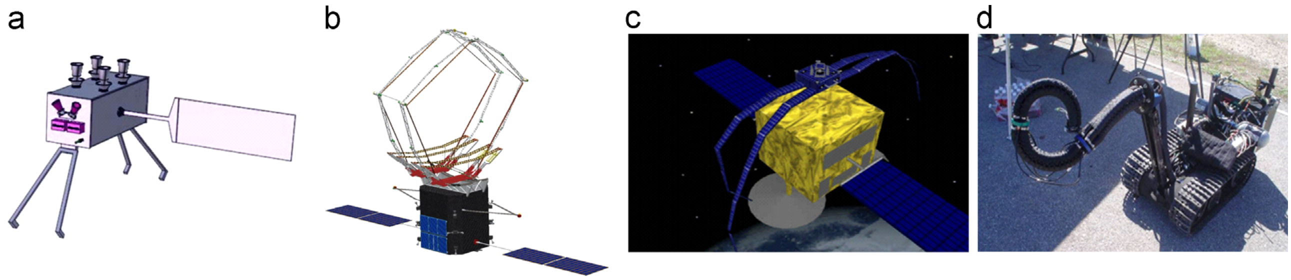

Fig. 2. Tentacles capturing: (a) e.Deorbit [12]. (b) CADET [15]. (c) TAKO [16]. (d) OctArm [17].

Orbital express of DARPA [21] and many others [22]. However, the targets in these missions are cooperative. For example, four markers are installed on the target satellite for rendezvous in ETS-7 mission. As what has been discussed above, space debris could be a non-operational satellite, an rocket upper stage or residuals from explosions. A space debris object will not provide any information to chaser satellite, and sometimes they are even tumbling. Therefore, it is more challenging to apply robotic arms in space debris removal missions as compared to on-orbit servicing missions.

To verify the process of capturing a non-cooperative and tumbling target, DLR has been developing robotic technologies in a mission named Deutsche Orbital Servicing Mission (DEOS). The client satellite to be captured represents a non-cooperative and tumbling target which does not provide any information for rendezvous and capturing. The entire process from far range rendezvous to deorbiting is, however, to be performed in this mission [23]. In order to simulate the contact behaviors during capturing and docking in space systems, DLR has developed a simulator called European Proximity Operations Simulator (EPOS). EPOS is a ground-based hardware-in-the-loop facility to test, e.g., the dynamic behavior while docking [24]. This simulation facility is able to simulate the docking and capturing processes from 25 to 0 m. Two KUKA robots represent service and client satellites respectively, and one of them slides on a pair of rails performing the approaching motion, the basement of the other one is fixed [25]. Zebenay has investigated the contact dynamics of inserting a probe into the nozzle cone of an apogee kick motor using a hybrid docking simulator primarily in one dimension. The hybrid docking simulator combines a hardware passive compliance between the probe and the kick motor with virtual contact dynamic model. This technology supports a non-operational satellite capturing [26]. DARPA developed the Front-End Robotics Enabling Near-Term Demonstration (FREND) program to demonstrate the robotics technology and perform unaided capturing. The FREND arm has been designed, assembled and tested. It shows a higher stiffness and accuracy than the robotic arms for the Mars Exploration Rovers, Phoenix Lander, Space Station and Space Shuttle [27]. Fig. 3 displays these three types of robotic arm capturing concept.

Various research areas related to robotic arm capturing have been investigated. The three most considerable areas are minimizing the impact influence, de-tumbling and attitude synchronization.

Minimizing the impact influence: Since contact between the service satellite and target is unavoidable when using robotic arm capturing method, one of the greatest challenges is how to minimize the impact influence. Flores-Abad described a method to minimize the attitude disturbance by controlling the direction of relative velocity between chaser and target passing through the mass center of the servicing system. The optimal time and the position for capturing are determined by a constrained nonlinear optimization procedure, and the Markov Chain Monte Carlo (MCMC) method is applied to solve the problem of uncertain boundary conditions [28]. Huang derived the mapping relationship between impact force and base force. This allows us to mitigate attitude disturbance during capturing by minimizing the impact force and optimizing the approaching trajectory. A Genetic Algorithm (GA) is used to optimize the parameters of joint trajectories [29]. Moreover, the configuration between the service satellite and target is another feature can affect the impulse influence [30,31]. Yoshida introduced the minimization of base attitude during three phases: approaching phase, impact phase and post-impact phase from the viewpoint of angular momentum distribution [32]. Papadopoulos proposed a concept of percussion point to minimize the impact force thus mitigating the disturbance to the service satellite base [33]. Larouche and Zhu presented a framework for capturing a non-cooperative target with the help of visual servoing. A Kalman filter is used to predict the motion of the target with respect to chaser satellite. However, at least three markers are needed using this method [34].

De-tumbling: A space debris object is always tumbling due to the residual angular momentum which brings a great trouble for capturing with a robotic arm. According to the research result from JAXA, tumbling rate below 3°/s can be captured easily; tumbling rate above 30°/s will not be regarded as a target; tumbling rate between 3° and 30°/s can be de-tumbled using brush contact [35]. A brush contactor, made of PTF, is able to release the residual angular momentum of the target by soft and static contact (Fig. 4). The impact influence on the service satellite is released by the joint virtual depth control. An Ion-Beam Shepherd, which is

Fig. 3. Single arm capturing methods: (a) DEOS [23]. (b) EPOS [25]. (c) FREND [27].

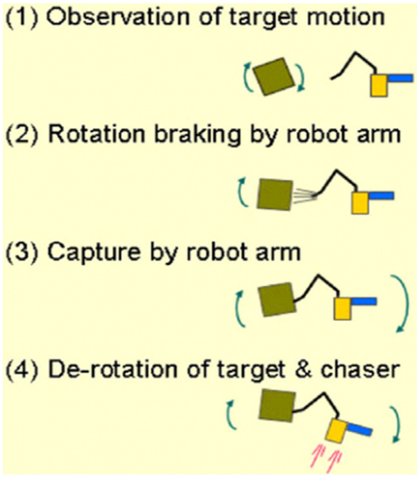

Fig. 4. Brush contactor [95].

Fig. 5. Multiple arms capturing ATLAS [40].

able to transfer the angular momentum, is also a choice for de-tumbling a target [36]. An optimal control concept of intercepting and de-tumbling a target with unknown inertia parameters, which is estimated by an Extended Kalman Filter (EKF) has been employed to capture a tumbling target [37].

Attitude synchronization: It is not necessary to de-tumble a target when its tumbling rate is relatively small. However, attitude synchronization, which to ensure the capturing point is always directed towards the service satellite, is an indispensable phase before capturing. To keep the capturing motion stable and efficient, it is a wise decision to keep a constant relative distance and attitude between service satellite and target coincidentally. An has developed an compound control method which consists of a nonlinear feedback control law and a sliding mode control to perform the attitude synchronization of docking to a tumbling target without knowing the bounded external disturbances [38]. Attitude synchronization contains two aspects, one is relative position tracking and the other is attitude reorientation. Subbarao has developed translation control law and attitude control law separately to execute the attitude synchronization [39].

2.1.3. Multiple arms capturing

Advanced Telerobotic Actuation System (ATLAS), a program from UK, consists of two robotic arms telerobotically controlled from ground [40] (Fig. 5). Multiple arms can be used in robotic assembling of a space structure, robotic refueling task and space debris removal [41]. Yoshida has investigated the kinematics and dynamics of dual arm in a free-flying robot, concluding that the second arm is able to stabilize the satellite [42]. Moreover, the second arm also makes the system flexible since it accomplishes a difficult task by cooperating with the first one.

2.1.4. Mechanical effector

A mechanical effector is one of the most important parts in a robotic arm. It is directly involved in the capturing motion and contacts with the target. The success of the space debris removal mission depends highly on the reliability and stability of a mechanical effector. Therefore, mechanical effector plays an crucial role in either single or multiple robotic arms capturing.

There are several concepts of mechanical effector for capturing a space debris object, such as a probe for the nozzle cone of an apogee kick motor, payload attach fitting (PAF) device, articulated hand, two fingers mechanism and universal gripper. Five mechanical effectors are shown in Fig. 6. The principle of a probe capturing is to expand the top of the probe to the inside surface of a nozzle cone after inserting the probe into the cone thus capturing the target. Based on this configuration, Yoshida and Nakanishi introduced the concept of virtual-mass impedance matching (VIM) model and it is applied in the collision modeling [43]. DLR has engaged in the Experimental Servicing Satellite (ESS) study which is supposed to inspect, approach, catch, dock and repair a non-operational satellite [44]. The visual servoing during capturing using the probe effector is tested on two robotic arms: one carries a mockup of a nozzle cone of an apogee kick motor and the other carries the probe mechanism and captures the mockup. A model-based vision camera guides the approaching step, and the force sensor takes over when the contact happens [45].

A V-flange in the rear of satellites exists as a mechanical interface with the launch adaptor. The V-flange (also called as payload attach fitting) grasping requires an open contact, i.e., the fingers keep open after capturing [46]. The grasp point, path planning of the end-effector and timeline considering the lighting conditions should be determined before capturing. Inaba introduced the image processing method of visual servoing, in which an algebraic curve-fitting technology is applied to recognize the largest arc as the outer circle of the V-flange. A three fingers hand with a camera is used in an experiment which verified the basic feasibility of this concept [47]. However, open contact remains the risk of pushing a target away.

The configuration of two fingers capturing mechanism is similar to the docking system of ETS-7. This mechanism forms a closed space before contact with the grapple fixture. From this respect, the contact is called closed contact to distinguish with open contact. Closed contact would not push the target away after the closed space is formed. However, the grapple fixture should be a ring which seldom exists on satellite in a perfect position for capturing. Xu proposed two modes of capturing process using two fingers end-effector from different observation frames: one is from inertial frame and the other is from space based (chaser satellite) or local frame. The autonomous path planning and visual servoing algorithm are tested on ground [48].

The dexterous hand for on-orbit service mission is developed by DLR as well. This articulated hand mimics powerful human hand in a certain degree. It is controlled by a tele-manipulation set-up and human operator [45]. The dynamic model of a single finger which contains 3 degrees of freedom can be established based on the robotics technology. However, grasping motion is completed by a collaboration between fingers and palm, i.e. the model of grasping motion is strongly coupled. A multi-finger dynamic model is derived to describe the interaction between fingers by Harbin Institute of Technology (HIT) [49].

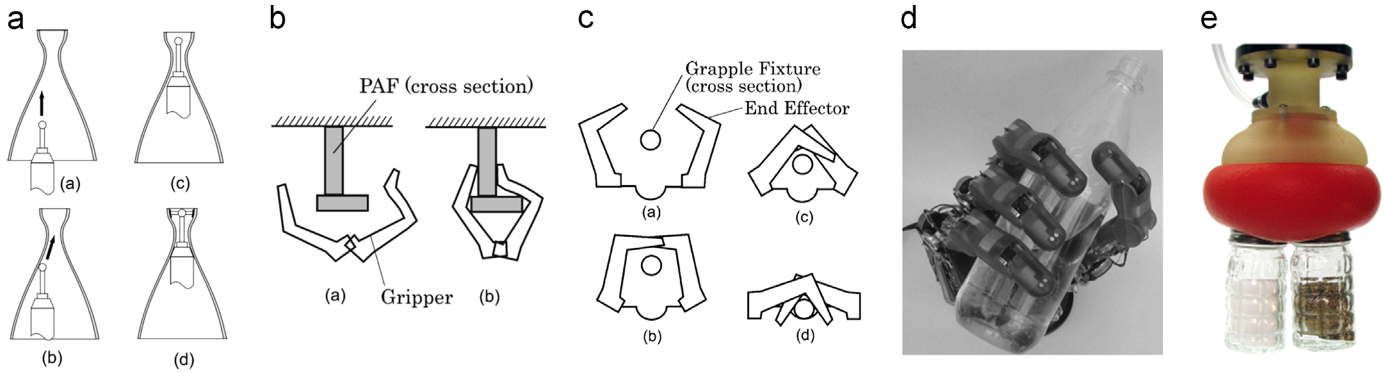

Fig. 6. Mechanical effectors: (a) Probe [43]. (b) PAF [46]. (c) Two fingers mechanism [46]. (d) Articulated hand [45]. (e) Universal gripper [50].

Universal gripper is able to treat complex shaped object using the deformation of granular material. The gripper is able to capture and release an object by vacuum-hardening and inflating the granular material encased in a membrane [50]. Several experiments have been executed to test its reliability. However, this gripper is not adaptive to capture a free-flying object since a force closure needs to be formed during capturing.

2.2. Flexible connection capturing

For tentacles capturing and robotic arm capturing, the connection between chaser satellite and target is stiff. This makes the composite controllable and stable. However, the mass and cost are dramatically increased. To overcome this drawback, flexible connection capturing methods in which the end effector and chaser satellite are connected by a tether, are proposed.

2.2.1. Net capturing

In order to mitigate the situation in GEO orbit, ESA has sponsored the Robotic Geostationary Orbit Restorer (ROGER) whose objective is to transport a target into a graveyard orbit. The end-effector in this project can either be a net or a gripper mechanism. Net capture mechanism consists of four flying weights in each corner of a net. The flying weight is always called bullet, which is shot by a spring system, named net gun. These four bullets help expand the large net thus wrapping a target up [51]. It is not necessary to priori know the mass, inertia and other physical figures during capturing using this method. ESA also issued e.Deorbit project, which they are confident to declare, it may be the first in-flight demonstration of active space debris mission [12]. Net capturing method is one of several concepts for ADR proposed in e. Deorbit project. The principle of net capturing in this project is similar to ROGER. Simulations with different parameters such as relative position, rotation, tether length, tether stiffness and others describe the dynamic characteristics of a net [52]. Parabolic flight experiments have been performed by GMV and ESA to validate the net deployment and capturing simulations [53]. At Politecnico di Milano Dipartimento di Ingegneria Aerospaziale (PoliMi-DIA), a project named Debris Collecting Net (D-CoNe) has been developed [54]. The net is modeled as a mass-spring system in the simulator, and several tests on ground have been performed with different bullet masses and gas pressure, concluding that the gravity can be neglected when the initial velocity is high enough. University of Colorado at Boulder has proposed a net concept called REsearch and Development for the Capture and Removal of Orbital Clutter (REDCROC) as well. The REDROC system is composed of inflatable booms structure and nets configured aside. Net capturing mechanism in REDCROC project works together with GOLD, a removal method which will be introduced in removal methods in this paper. Thus, no propulsion system is needed using this capturing mechanism. The objective dimension of a space debris object in this project is 30 cm in diameter, and the whole system can be scaled when choosing a larger debris [55]. Four different concepts are provided in Fig. 7.

Net capturing is regarded as one of the most promising capturing methods due to its multiple advantages e.g., it allows a large distance between chaser satellite and target, so that close rendezvous and docking are not mandatory; it is flexible, light weighted and cost efficient. However, several research areas related to net capturing such as modeling of a net, contact influence, deploying process investigation and tumbling compatibility still need to be developed.

Modeling of a net: Modeling of a net is an indispensable step to investigate the dynamic characteristics of net capturing system in a simulator. Before establishing a dynamic model of a net, the physical properties of a net should be addressed. Since the net material is required to be light, strong and tough, Zylon, Dyneema, Kevlar and Vectran are the material candidates [56]. Based on the previous studies on space webs, a quadrangular mesh is suggested because it revealed to be the optimum both on mass and stiffness [57]. The ratio between the square mesh dimension l and the net side length L is another important parameter. A good compromise in terms of stiffness and mass turned out to be $k=l/L$ between 1 and 5%. Based on numerical simulations of net casting and disposal strategies that a 1 mm knotted Kevlar net can carry out all the necessary operations with target up to 1000 kg without failures [56].

Various dynamic models of a net have been discussed, such as mass–spring model [58], absolute nodal coordinate formulation [59], elastic continuum model [60] and cubic B-spline model [61]. Mass–spring model is the most commonly applied modeling method among them. In a mass–spring model, a tether is usually assumed to be formed by several small pieces. Since a net is composed of many small square meshes, the interaction knot is simplified as a mass point, and the tethers between these knots are regarded as spring–damping elements. As early as 1988, Carter and Greene have proposed a bead model to simulate a tether between a mother satellite and a daughter satellite. The tether is assumed to be comprising of several beads connected by spring and dashpots [62]. This model is called bead model or initial mass–spring model. Sidorenko and Celletti investigated the periodic motions of a tether satellite system using the mass–spring model [63]. The dynamic equations of this model are linear ordinary differential equations. However, the accuracy of this model is not as good as the other modeling methods and it cannot describe the nonlinear and large deformation of the tether. To overcome this drawback, absolute nodal coordinate formulation (ANCF) for modeling a net has been proposed by Liu [59]. The mass matrix is constant and symmetric since absolute displacement and global slopes are applied as element coordinate using ANCF. To further

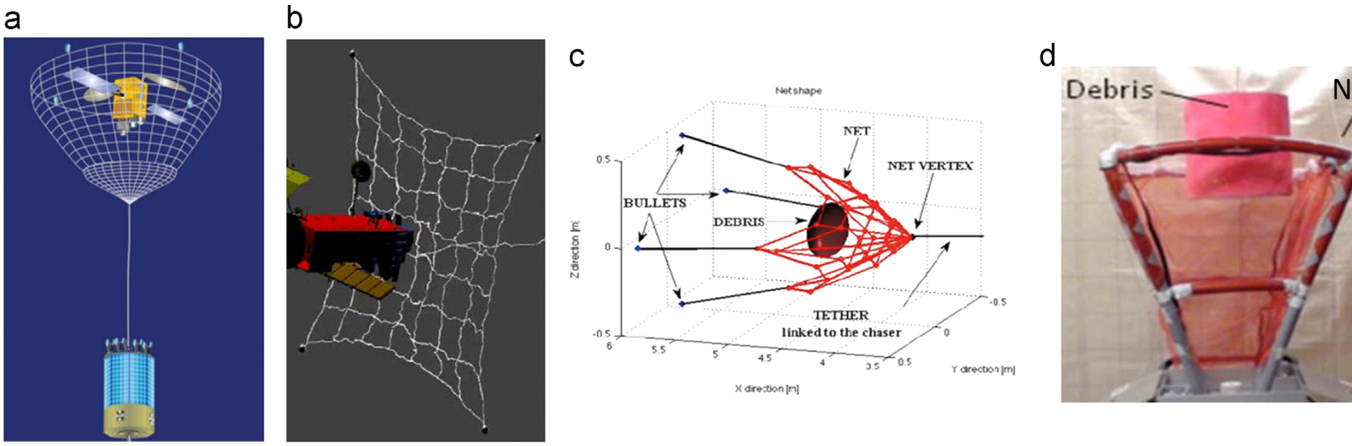

Fig. 7. Net capturing: (a) ROGER [51]. (b) e.Deorbit [12]. (c) D-CoNe [54]. (d) REDCROC [55].

increase the accuracy of a tether modeling, Mankala and Agrawal developed dynamic regulations of a tether under three conditions based on the elastic continuum model: (a) unchangeable tether length on ground (2) changeable tether length on ground (3) changeable tether length in orbit. Hamiltons principle and Newtons law are applied to establish the dynamic equations in these three conditions, respectively. The models derived from these equations are proved to be reliable by comparing two sets of simulation results [60]. Koh and Rong investigated the dynamic characteristics of a large displacement cable motion using the elastic continuum model and validated the model through experiments [64]. Since an elastic continuum model consists of partial differential equations, researchers are investigating the dynamics of a single tether or cable and no one has ever integrated tethers into a net due to the complexity. Model complexity and time consuming when calculating are fatal disadvantages using an elastic continuum model. The net capturing method for space debris is originally from the concept of fishing net applied in marine fishery. However, the number of physical nodes of a fishing net usually exceeds three millions and the net was modelized by a set of rigid bars [65]. To simplify the net model and make the bridle and surface go smoothly and continuously, cubic B-spline curve interpolation is applied to simulate fishing net which is shown in Fig. 8.

Contact influence: During the net capturing process, contact between a net and a target is unavoidable. The fragile part of a space debris can, however, be destroyed and departed into other space debris if inappropriate contact is made e.g., the bullet is shot on the debris and more space debris might be generated in this case. Even worse, the mission may come into a failure due to an improper wrapping up. Since to avoid generation of new space debris is a crucial criteria for an ADR project, the contact effect between a net and a target is worth being investigated. Two impact influence methods have been introduced so far. One is inelastic collision by assuming that the point mass is far less than the targets, the other is elastic collision [66]. A deformation energy method is always applied to describe impact behavior [67].

Deploying process investigation: When a net is cast from a chaser satellite, the bullets can be shot in different combinations of velocities and/or angles. Inappropriate combination of shooting velocity and angle might lead the deployment chaotic. The most efficient and effective way to deploy the net is another promising topic as well.

Tumbling compatibility: Net capturing does not require highly accurate GNC and the combined system after capturing re-enters via controlled Δv, which lower the difficulty of close range rendezvous beforehand and the removal afterwards. In order to simplify the analysis, a space debris object is always considered as a stable target when using net capturing method. However, a space debris object is usually tumbling because of its residual angular momentum thus increasing the difficulty of capturing. The possible solution is either capture a tumbling target directly or install a de-tumble device on chaser satellite. It is costly and time consuming using robotic arm capturing from this respect, because attitude synchronization must be performed before capturing so that the target is relative stable to the chaser. Net capturing can overcome this defect by being compatible with the tumbling space debris and no attitude synchronization is needed [68]. However, the acceptable tumbling range of a target is not yet understandable. Moreover, a target is non-cooperative which means less information of the target is prior known, e.g., the direction of the tumbling axis is unsure. A net might be twined by a high tumbling angular velocity thus leading the combined system uncontrollable. An acceptable tumbling limitation and methods to stabilize it are to be investigated.

2.2.2. Tether–gripper mechanism

The tether concept used in space was first proposed in 1960s

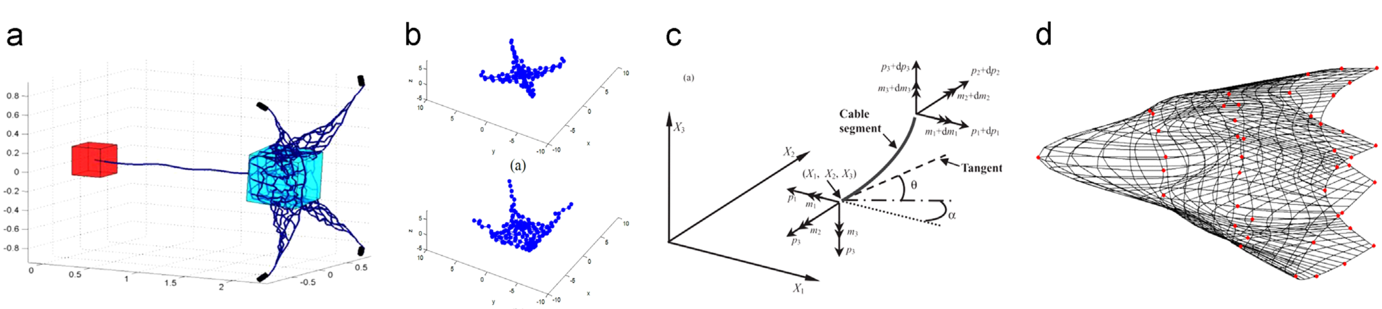

Fig. 8. Modeling of a net: (a) mass–spring model [58]. (b) ANCF [59]. (c) Continuum model [60]. (d) Cubic B-spline model [61].

with an idea of space elevator which is inspired by Eiffel Tower [69]. It brought a wide discussion about the available material, which is considered impossible until the discovery of carbon nanotube in 1991 [70]. With the development of space technology, many space concepts and/or missions have been proposed or implemented using tethered space robots, such as cargo transfer between spacecraft, space debris collection, upper atmospheric research and geomagnetic field investigation [71].

The tether–gripper is the other mechanism introduced in ROGER besides net (Fig. 9). The principle of the tether–gripper mechanism is similar to the net capturing mechanism. The end-effector in the tether–gripper mechanism is shot as a 3-finger gripper to capture a target [51]. The 3-finger gripper is designed to be able to catch a specific part of the target precisely and stably which leads to the requirements for tether–gripper mechanism more stringent and more complicated than net capturing in operation. Huang proposed a tethered system called Tethered Space Robot (TSR) [72] and he has deeply investigated the tethered gripper robot for active debris removal in various areas, including visual servoing technology [73], coordinated orbit and attitude control [74,75], post-capture control [76,77], and de-tumbling composite [78,79]. Visual servoing technology is developed to recognize and track a space debris object accurately since a non-cooperative target is shown as a small image in the charge-coupled device (CCD) camera. A novel template matching method called Normalized SAD has been proposed to detect the appointed template with a high accuracy [73]. In approaching phase, the coordinated control of the orbit and attitude simultaneously is quite challenging and complicated. Wang and Huang have developed a novel scheme to realize this by adjusting the position of the attachment point and using the thrusters [74]. The optimal trajectory to approach a target based on velocity impulse has been studied using an improved non-dominated sorting genetic algorithm (NSGA-2) [80] and Gauss pseudospectral method [81], respectively. Meng and Huang also provided an approaching model and two controllers for close range rendezvous, one of which is optimal open-loop controller and the other is feedback controller [82]. Post-capture attitude control is also challenging since the movement of combination system (chaser satellite and target) is unpredictable. In Ref. [76], a coordinated controller comprised by two controllers is designed. These two controllers can be switched under an optimized switching condition to reduce the fuel consumption. Based on simulations, yaw and pitch motions have a faster convergence speed than the roll motion since a greater torque from tether tension can be obtained [79]. In addition, the tumbling tethered space robot-target combination can be stabilized by this controller as well. Before the de-orbiting phase, parameters estimation, such as mass and inertia parameters, of a non-cooperative target is a crucial step to ensure the controllability. Zhang introduces an scheme of inertial parameters estimation using the tether force, which includes a coarse mass estimation during post-capture, a mass estimation scheme during the first stage of retrieval and an inertia and offsets estimation during the middle stage of retrieval [83]. When the chaser satellite travels with the target to re-enter using tethered system, it is risky that a collision happens between chaser satellite and target if improper movement is performed. Parameters, such as physical properties of the tether, inertia of the target, tether tension force and initial conditions would affect the re-entry. Based on the research from Aslanov, the tether has to be tension all the time to ensure a safe transportation during re-entry, and the force vector of the chaser satellite should coincide with the tether direction [84]. However, the reliability of tethered gripper capturing and the contact effect between gripper and target are insufficiently understood. More researches related to this subject are expected.

2.2.3. Harpoon mechanism

A harpoon mechanism with barbs on its tip can be shot from chaser satellite and penetrate itself into a large space debris object. Chaser satellite will pull the debris re-enter or to a graveyard orbit afterwards. It is considered as an attractive capturing method because of its compatibility with different shaped targets, stand-off distance allowed and no grappling point needed. Since penetrating happens in this case, the risk of generating new space debris is relatively high. Moreover, it is not capable to treat a target with high tumbling rate. A Grappling System (GS) has been proposed by Astrium (Fig. 10). Some experiments and tests have been operated on ground [85]. Tiny fragments are generated through penetrating in these experiments. Different sizes of fragments are generated with different shooting angles to a flat aluminum plate. Since the fragments will stay inside the target, they believe that the debris generating is not a fatal issue. Harpoon capturing method is also one of the concepts from e.Deorbit. Based on the trade off results with net method by ESA, harpoon mechanism earned a higher score since cost efficiency and higher Technology Readiness Level (TRL) can be obtained [52]. Even though net method has a better system performance and less physical constraints, harpoon has still been suggested by ESA due to its easiness to be tested on ground [86].

3. Removal methods

Removal methods are fundamentally different from the capturing methods. In some cases, removal is performed after capturing. However, in most cases, removal methods avoid capturing at all. The concept diagram of the existing removal methods is shown in Fig. 11.

The most relevant and promising removal methods are drag augmentation system (DAS), electro-dynamic tether (EDT),

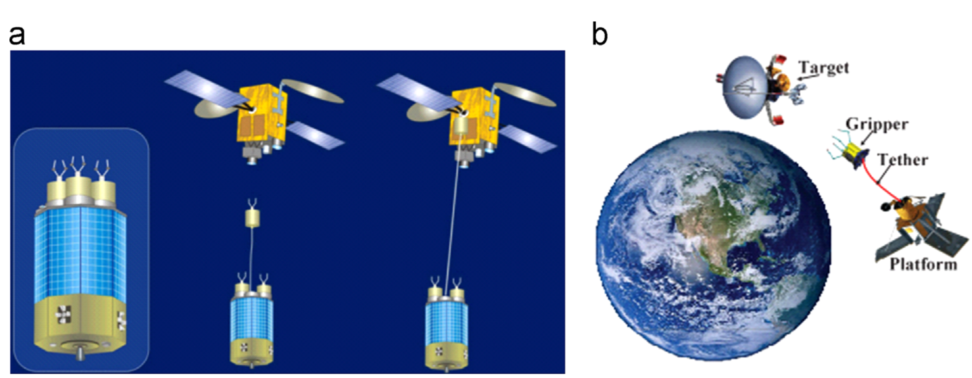

Fig. 9. Tether–g ripper capturing: (a) ROGER [51]. (b) TSR [72].

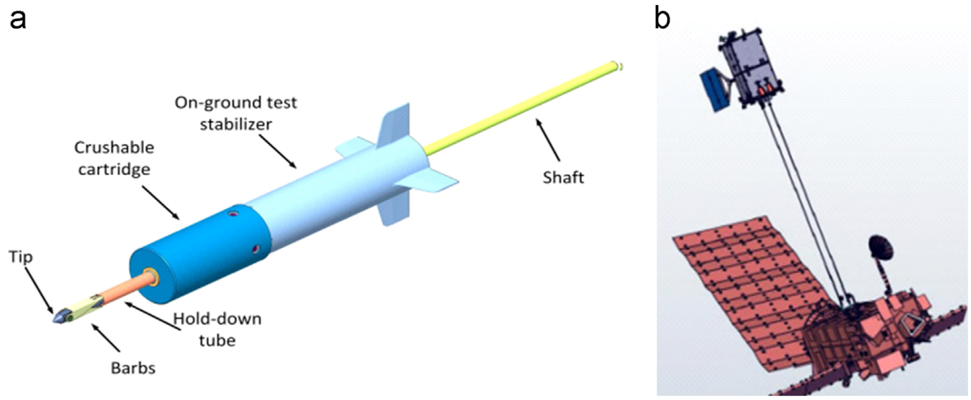

Fig. 10. Harpoon capturing methods: (a) GS harpoon [85]. (b) e.Deorbit [52].

contactless removal methods and contact removal methods. To clarify their characteristics and draw a comparison between them, their respective examples, original sources, advantages and drawbacks are summarized in Table 3.

3.1. Drag augmentation system

Increasing the area-to-mass ratio of a space debris object is a way of increasing the atmosphere drag influence. Drag augmentation method allows a large distance between chaser satellite and target. Therefore, no close range rendezvous or docking is required in this method. It reduces the requirements for chaser satellite since the reentry process is performed by the atmosphere drag influence instead of chaser satellite. In addition, it is compatible with different sizes of space debris. Due to the atmosphere distribution in space, the targets removed using this method should be orbiting in LEO. Three methods to remove space debris based on this concept are introduced as follows (Fig. 12).

3.1.1. Foam method

After a chaser satellite rendezvous with a space debris object and flying around it, the foaming process is executed as following: foam is ejected from the ejection device installed on the chaser onto the target and stick onto it, then foam covers the whole target and turns it into a foam ball. The area-to-mass ratio is increased due to the small density and large volume of the foam [87]. However, the foam should be stiff enough so that the foam ball will not be destroyed by small pieces of space debris and new space debris will not be generated. A combination of foam ejecting system and electric propulsion system is proposed in order to enhance the efficiency of debris removal, i.e., multiple targets will be removed in one mission by successively targeting space debris objects using the electric propulsion system and the chaser satellite will de-orbit itself with the same propulsion system when the mission ends [88]. The optimum foam material and de-orbiting period are still under discussions.

3.1.2. Inflated method

The concept of inflated method is similar to the foam method introduced above. An inflated ball replaces the foam ball in this method. Gossamer Orbit Lowering Device (GOLD) is a typical example under this concept. A large, lightweight, and inflatable envelop, which reduces object ballistic coefficient by up to two orders of magnitude during re-entry, can be either attached onboard or on a space debris object. Based on risk analysis, GOLD offers lower risks in terms of large debris generation and disabling other operational satellite compared with propulsive de-orbit methods [89]. However, the fatal disadvantage is that the mission will be failed if the inflated ball is destroyed by small pieces of space debris. Another similar idea is proposed in a patent which uses a device with three inflatable fingers catches the target before the ball is inflated [90].

3.1.3. Fiber-based method

When the material for expanding a space debris object is changed from foam to fiber, the space debris removal method becomes fiber-based removal method. The principle of fiber-based removal method is the same as the above discussed methods. The fiber is extruded by a heat source and wound around a target to intercept and expand it thus increasing the area-to-mass ratio [91].

3.2. Electro-dynamic tether

Electro-dynamic tether removal method is originally used in orbit transfer and orbit maneuvering [92]. It is a method taking advantage of the geomagnetic field to reenter (Fig. 13). In this aspect, propulsion system is not mandatory during re-entry. In contrast, two practical drawbacks for this concept are it cannot treat targets beyond LEO due to the insufficient magnetic intensity; the other is that Lorentz force depends largely on the current goes through the tether, therefore the thrust is not large enough to realize orbit transferring when the current is low [93]. When performing space debris removal using electro-dynamic

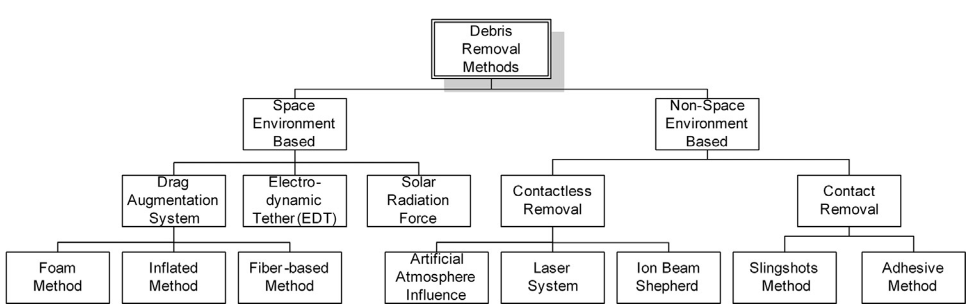

Fig. 11. Concept diagram of removal methods.

Table 3
Overview of relevant removal techniques.

Removal methods	Advantages	Drawbacks	Examples	Sources	Reference
Drag augmentation system	1.Allows a large distance	1. Risk of breakup	Foam	ESA	[87]
			Inflated	GAC	[89]
	2. Compatible with different size of debris	2. Less efficient	Fiber-based	US-Patent	[91]
Electro-dynamic tether	1. No need for propulsion system	1. Capture needed	EDT	JAXA	[95]
	2. High TRL	2. Unavailable in GEO			
Contactless removal	1. Allows a long distance	1. Less efficient	Artificial atmosphere	US Patent	[108]
	2. Compatible with different sizes of debris	2. Unavailable in GEO	Laser system	LODR	[111]
			Ion beam shepherd	ESA	[115]
Contact removal	1. Multiple targets removed	1. Rendezvous needed	Slingshots	USA	[120]
	2. Short working period	2. Complex control system	Adhesive method	Astroscale	[123]

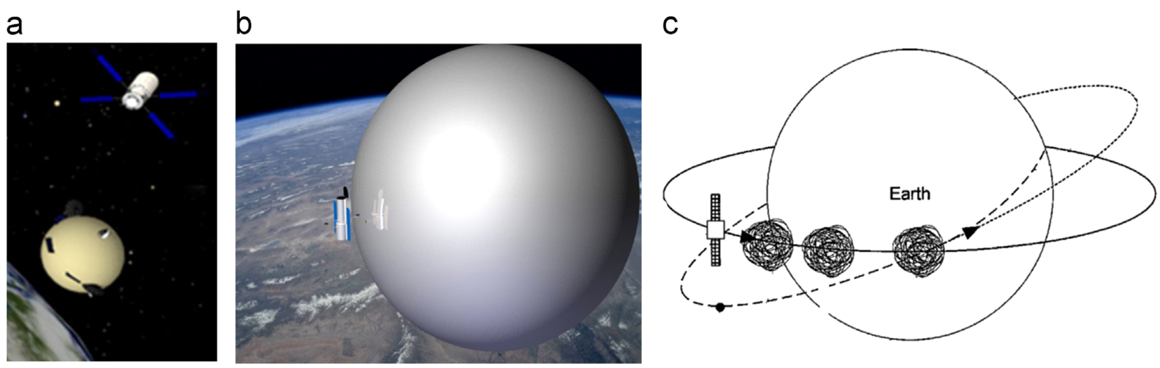

Fig. 12. Drag augmentation methods: (a) foam method [87]. (b) Inflated method [89]. (c) Fiber-based method [91].

tether, a space robot firstly captures a target using robotic arm or harpoon and installs an extendable electro-dynamic tether on it. The Lorentz force generated from the interaction between the electric current flowing in the conductive tether and the geomagnetic field is exploited to decrease the space debris object [94]. EDT package is composed of a bare conductive tether and two filed emitter array cathodes. One collects electrons and the other emit electrons in which way current is generated [95]. The space robot can slide to another space debris object after installing the EDT on one object. However, capturing is indispensable, which indicates robotic arm technology is applied in this method. To investigate the characteristics of EDT, such as tether stability and deployment dynamics, numerical simulation is performed by Kawamoto. Lumped mass is used to model the tether and the tether flexibility is taken into account [96]. Electro-dynamic tether is prone to libration instability due to the complex space environment, such as periotic changing in geomagnetic filed, lunisolar gravitational attractions and Earths oblateness. Kojima has studied the in-plane libration instability in elliptic orbit experimentally based on delayed feedback control [97]. Inarrea used the same control theory to analyze the attitude stabilization of the electro-dynamic tether in inclined orbit [98]. Related to the numerical simulation by Zhong, out-of-plane libration plays a more significant role in libration instability than in-plane libration does, and it in turn affects the in-plane libration through model coupling. Based on this understanding, the libration instability is able to be stabilized by exclusively control the out-of-plane libration [99]. The material for the tether is still under discussion since it should survive the extreme space environment during the whole de-orbiting period [100].

3.3. Solar radiation force

Solar sail propulsion method was first validated by JAXA in 2010 [101]. Several solar sail propelled missions have been discussed in detail by Johnson and Young [102]. Using solar radiation force to remove space debris is a method for the non-operational satellites whose propulsion system fails or the propellant is not enough to reenter, but whose control system for solar sails is still working. Since the semi-major axis of a satellite increases when it moves along its orbit away from the sun, and in turn it decreases

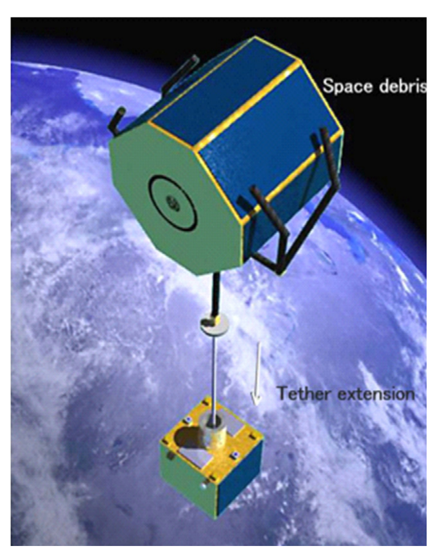

Fig. 13. EDT from JAXA [95].

when it moves towards the sun. The net change of the semi-major axis is zero in one full orbit. Based on this effect, the orbit can be lowered by rotating the solar sails at appropriate time to receive the solar radiation force, i.e., satellite rotates its solar sails fully face the sun when moving towards it, and make it parallel to the sun light when moving away from it. The concept of this method is shown in Fig. 14. According to the analysis by Borja, it will take no less than 5.8 years to de-orbit a geosynchronous satellite to a recommended altitude 235 km proposed by the Inter-Agency Debris Coordination Committee [103]. This method, however, depends highly on the solar sails driving capability. In order to overcome this drawback, Lucking proposed a passive removal method: a combination of exploiting solar radiation pressure, Earth oblateness and aerodynamic drag [104]. Since the solar sail propulsion is considered not applicable for altitude below 750 km due to the atmospheric density, the solar radiation pressure is used to decrease the altitude from a significantly high orbit and aerodynamic drag takes over when the debris is in a low altitude. Macdonald analyzed that the steering law for satellites in equatorial orbits and polar orbits concludes that the steering law of polar orbit is more efficient than that of equatorial orbit [105].

3.4. Contactless removal methods

Contact between chaser satellite and target during capturing and removal will influence the stability of the entire system, e.g., it may push the target away from the chaser or make the system uncontrolled. Contactless method, which means no direct contact happens during the entire removal process, can overcome these defects (Fig. 15). However, it always takes a long time to remove a target. The most relevant contactless removal methods are artificial atmosphere influence method, laser system and ion beam shepherd. The general principle of all these methods is to decrease the velocity of space debris thus lowering their altitudes by ejecting some medium objects in their trajectories.

3.4.1. Artificial atmosphere influence

The principle of artificial atmosphere influence is to propel atmospheric particles in the path of a debris object. As a result, the velocity of the debris is decelerated and its altitude is lowered. Types of the atmosphere particles can be gaseous plume or a vortex whose ejecting direction is orthogonal to the path of the debris [106]. Kofford designed an artificial atmosphere delivery system composed by combustible propellant and an ignition device [107]. To create a transient gaseous cloud which has sufficient density in front of a debris to help it re-enter is another analogous concept [108]. Artificial atmosphere influence is a green removal method since the gaseous plume is no harm to operational satellites and it will eventually fall back to the atmosphere. This technique is considered as one of the most promising removal methods [109].

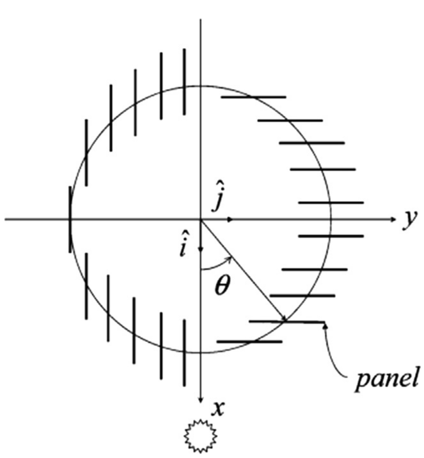

Fig. 14. Concept of removal method using solar radiation force [103].

3.4.2. Laser system

Laser system is available for both large and small space debris removal. Pulsed laser beam shoots onto a space debris to decrease its velocity and lower its altitude. However, the risk of new debris generation is significantly high using laser system. As early as 1996, Phipps stated that a space debris object can be removed by a 20 kW, 530 nm, Earth-based, repetitively pulsed laser. The system called ORION consists of an Earth-based laser system to generate powerful laser beam and a high-resolution detection system to chaser targets with a diameter of 1 cm below 500 km. According to Phipps' research, this system is able to remove all space debris whose size is larger than 1 cm and whose mass is less than 500 kg below 1000 km altitude in 4 years [110]. An updated system called Laser Orbital Debris Removal (LODR) is able to de-orbit the Envisat by 40 km every 8 weeks. This laser system can be located at ground-based equator, ground-based polar region or on board [111]. Since the behavior of a target is shape dependent when beaming the laser on the surface of it, Liedahl has investigated the dynamic behaviors of different ejected shapes, including cube, sphere, plate, spinning plate and cylinder [112]. To enhance the laser operation time on a target, the orbital information of the target is required to be accurate. Bennett has improved the orbit prediction accuracy by using the long term two line elements (TLE) data and data tracked from two passes over 24 h by laser [113].

3.4.3. Ion Beam Shepherd

Ion Beam Shepherd (IBS) is a concept of ejecting highly collimated neutralized plasma beam onto a debris object thus lowering its altitude. It is another contactless removal method, so no solid contact happens throughout the removal process and it will not bring the contamination problem since the plasma will eventually fall back in the atmosphere. The similar problem as the laser system also happens to IBM, which is the shape dependency between the plasma and the target interaction. Bombardelli has investigated the dynamical response of sphere and cylinder shaped debris [114]. He optimized the system by minimizing the mass of a shepherd [115]. A distance between a chaser satellite and a target keeps at 10–20 m. As a result, a second propulsion system is needed to keep this distance. Merino has developed a simulator called Ion Beam Interaction Simulator (IBIS) to analyze, test and validate the conceptual design of IBS. In addition, it is able to evaluate the performance of the system, optimize design parameters and make the deorbiting strategies [116]. He also analyzed the propulsion requirements, identified the plasma beam characterization and investigated the momentum transmission to the space debris during the interaction between plasma and target [114]. Even if the LEO region contains most of space debris, the space debris in GEO should not be left out. Kitamura suggested using IBS to re-orbit space debris in GEO. By their numerical analysis and some experimental facilitation, they concluded six GEO debris can be removed during 170 days using a 2500 kg shepherd [117]. The concept of ion beam shepherd is also available in astrodynamics, such as asteroid deflection to avoid a catastrophic collision with Earth [118] and de-spinning an asteroid [119].

3.5. Contact removal methods

Contact removal method is a concept that takes advantage of a direct interaction between chaser satellite and target during the

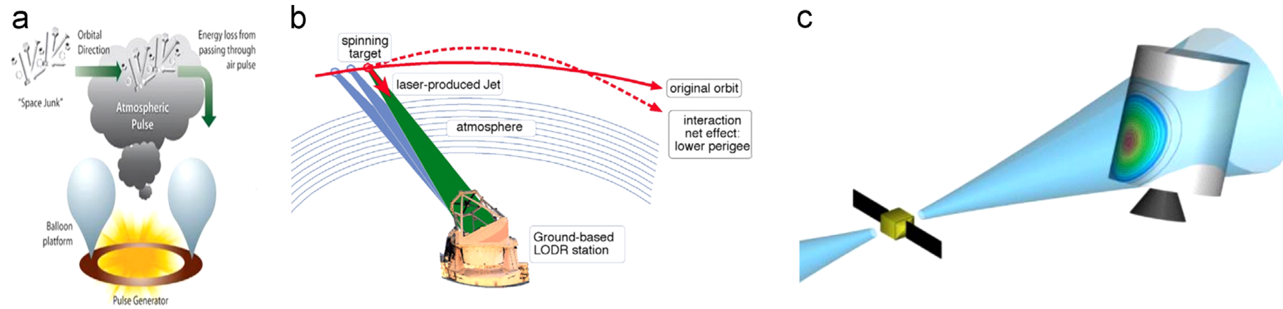

Fig. 15. Contactless removal methods: (a) Artificial atmosphere [108]. (b) Laser system [111]. (c) IBS [115].

removal process. Slingshot method and adhesive method are two typical removal approaches under this category (Fig. 16).

3.5.1. *Slingshot method*

Texas university has developed a satellite called Sling-Sat Space Sweeper (4S), which is designed for saving energy for ADR since it removes multiple targets in one launch. The satellite can capture a space debris and eject it towards the earth then slide to another space debris object applying the momentum generated from the ejection [120]. 4S is composed of two collectors connected by two deployable masts, tri-scissors in this case. When slinging space debris object the sling-sat undergoes four configurations which are capture, spin-up, expulsion and return. A contact takes place when one of the collectors is plastically capturing a target. Missel has derived the mathematical models based on angular momentum conservation theory for these four configurations by considering the sling-sat as a 2-mass system. For improvement, a 5-mass mathematical model for the configurations is established as well [121]. The path a sling satellite travels between several debris is optimized using genetic algorithm to select the maneuver order for the targets [122].

3.5.2. *Adhesive method*

Adhesive method is proposed by Astro Scale in Singapore and it is a multiple targets removal method as well. A de-orbiting kit, called boy, equipped with propulsion system can be released from a carrier, called Mothership. The boy adheres onto a tumbling space debris then removes it from its original orbit. Six boys are loaded on the mothership. Mothership sails to different space debris and release one kit each time, so that multiple targets can be de-orbited in one launch. On the front part of the boy, a plate with silicon adhesive compound is installed through a universal joint which contains 20° allowance to passively adjust the adhesive plate onto a flat surface of a target. In this case, a target whose tumbling rate is below 1–2°/s is an objective target. The boy is able to approach the tumbling target in two ways: along its tumbling axis and orthogonal to the tumbling axis. No matter which way is selected, an attitude synchronization is indispensable step before adhering onto a target [123]. JPL has also been developing a gecko adhesive grappling tool that uses microscope angled hairs to stick to the surface of a target. The adhesion is based on van der Waals forces and can be turned ON and OFF by controlling the loading direction [124].

4. Non-cooperativeness analysis

Space debris removal missions have some similarities with on-orbit servicing missions. However, in most on-orbit servicing missions, the target to be served is always cooperative, i.e., some physical fixtures on the target help the rendezvous and/or docking process. The geometry information, such as the Center of Mass (CM) or the inertia of the target, is prior known as well. On the contrary, space debris can vary widely in characteristics, e.g., rocket upper stages, non-operational satellites or residuals from explosions or collisions. They would not provide any information to chaser satellite since they are non-cooperative targets which makes ADR more complicated. Various space debris capturing and removal methods have been proposed and investigated so far. The non-cooperative levels of each debris are different based on their characteristics. The most appropriate capturing and removal methods for each debris should be different. As a result, the non-cooperative levels of debris and the tailored associated capturing and removal methods need to be developed.

A non-cooperative target can represent a body without any reflector on it for close range rendezvous. When capturing action is performed, a non-cooperative target can represent a body without a docking mechanism or without knowing its physical properties. In this aspect, non-cooperative target has different definitions in different situations, and it is possible to misunderstand the characteristics of a target if the definition is not made properly. Xu regarded a non-cooperative target as one without either artificial markers for cooperative measures or any grappling fixture for capturing. A triangular solar panel support is chosen as the capture fixture in his analysis. Pose measurement and 3-D

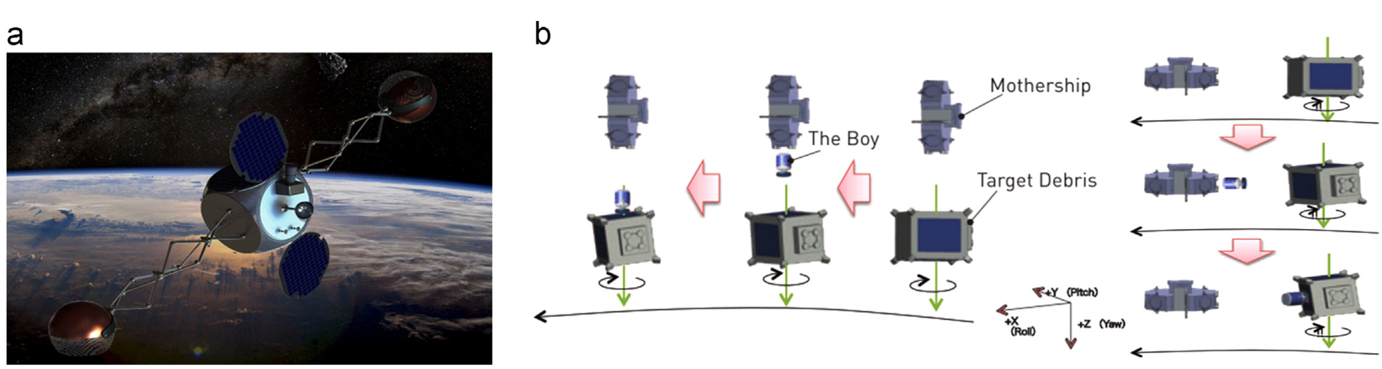

Fig. 16. Contact removal methods: (a) Slingshots [121]. (b) Adhesive method [123].

Table 4
Categories of non-cooperativeness for capturing.

Categories	Physical properties	Docking interface	Characteristics	Examples
A	Known	Extant	Fully known	Dysfunctional satellite
B	Known	Non-existent	Compatibility-restricted	Rocket stages
C	Unknown	Extant	Dockable and unpredictable	Foreign satellite
D	Unknown	Non-existent	Opaque	Fragmentation debris

reconstruction are performed to capture the target [125]. Thienel defined a non-cooperative target as a body not capable to maintain or transfer the attitude information. An method for estimating the body rate of the target is tested on the Hubble Space Telescope (HST) based on this definition [126]. Here in this paper only the non-cooperativeness for capturing phase is discussed. We define it from two aspects: physical properties of the debris are prior known or not, and docking interface exists or not. Based on this explanation, four different categories of non-cooperativeness are obtained with each example provided in Table 4.

Each level of space debris has its own difficulty to be removed. Therefore, various aspects should be concentrated when dealing with space debris in different categories. For example, when space debris in category B is selected as a target, a capturing method without any need for a docking interface, such as net capturing method, is more appropriate than robotic arm capturing. In this case, the control subsystem for the tethered-net satellite is complex because of the changing mass center and unpredictability of the composite system. It is also challenging to control the composite system in category C since the physical properties such as the mass, inertia of the target is unclear.

Some removal methods can only be performed after capturing, e.g., transporting a target to graveyard target. On the contrary, some removal methods avoid capturing at all, e.g., drag augmentation system. For space debris objects in different categories, the tailored associated capturing and removals methods are provided in Table 5. Take space debris in category D for example, nothing information about the debris is prior known, it is wise to choose the net capturing method to collect it since the compatibility of net capturing is higher than other capturing methods. The space debris object can be de-orbited or sent to graveyard orbit after capturing. Drag augmentation system, contactless or slingshots methods are choices for removal if no capturing is involved.

5. Conclusion

Many enabling techniques for ADR have been developed in the past two decades. To provide a clear impression of the existing techniques for ADR, in this paper, frameworks of methods for space debris capturing and removal have been developed. The advantages and drawbacks of the most relevant capturing and removal methods have been addressed as well. Moreover, a comparison between the existing technologies on ADR is drawn. The state-of-the-art related to these methods are discussed in detail.

To facilitate the development of space debris removal, research areas related to each capturing or removal method, such as minimizing the impact influence, attitude synchronization and modeling of a net have been discussed. In addition, research areas to be developed related to each capturing or removal method, such as tumbling compatibility research, net deploying process investigation and de-tumbling with IBS have been prospected.

Table 5
Tailored associated capturing and removal methods.

Categories	Capturing methods	Removal methods after capturing	Removal methods without capturing
A	All	De-orbit/to grave orbit/EDT	DAS/contactless/contact
B	Tentacles/net capturing/Harpoon	De-orbit/to grave orbit/EDT	DAS/contactless/contact
C	All	De-orbit/to grave orbit/EDT	DAS/contactless/contact
D	Net capturing	De-orbit/to grave orbit	DAS/contactless/slingshots

This paper also found that it is still challenging in the development of ADR for non-cooperative targets. Capturing and removing a tumbling target or a space debris object with unknown physical properties is still facing many technical challenges. This paper provides a non-cooperativeness analysis. Space debris objects have been categorized into four groups based on their non-cooperativeness. The characteristics and examples of each category have been clarified and provided. A tailored associated capturing and removal methods for each category have been addressed to facilitate decision-making through these existing capturing and removal methods.

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