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Review article

Emerging strategies in close proximity operations for space debris removal: A review

Muneeb Arshad [a,b], Michael C.F. Bazzocchi [b,c,*], Faraz Hussain [a]

[a] Department of Electrical and Computer Engineering, Clarkson University, 8 Clarkson Avenue, Potsdam, NY 13699, USA
[b] Astronautics and Robotics Laboratory (ASTRO Lab), Department of Mechanical and Aerospace Engineering, Clarkson University, 8 Clarkson Avenue, Potsdam, NY 13699, USA
[c] Astronautics and Robotics Laboratory (ASTRO Lab), Department of Earth and Space Science and Engineering, York University, 4700 Keele Street, Toronto, ON M3J 1P3, Canada

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ABSTRACT

Space debris removal remains a leading issue for space missions due to the rapidly increasing number of objects in low earth orbit that pose a substantial risk of collision with spacecraft. Space debris removal is necessary to reduce the probability of on-orbit collisions and reduce the potential for mission failure of active spacecraft. Various active and passive methods have been proposed to remove or deorbit space debris. Active methods include the use of tentacles, robotic arms, nets, tethers, harpoons, lasers, deorbiter modules, ion beam shepherds, foam-based, and sling-sat methods, while passive methods include the use of drag sails and solar sails. While active debris removal methods have great potential, they also have inherent risks related to target fragmentation, challenges with deployment and control, and complicated close-proximity operation phases. In terrestrial applications, new strategies have emerged to address risks of fragmentation during object capture or manipulation, such as soft grippers, as well as to improve path planning and control during remote close-proximity operations, such as through virtual and mixed reality systems. This paper reviews prominent active space debris removal methods, techniques employed during close proximity capture operations, as well as promising terrestrial gripping technologies, control schemes, and teleoperation strategies for space applications. In order to effectively capture, detumble, and deorbit space debris using contact-based methods, such as robotic arms or tethered grippers, it is essential to have accurate knowledge of the debris' geometric and inertial properties. and, thus, recent efforts in inertial parameter estimation are presented and discussed. Furthermore, operational and control strategies for space debris removal are investigated starting from traditional schemes, such as teleoperation, to emergent approaches derived from terrestrial control technologies, such as virtual and mixed reality.

1. Introduction

The continual growth of objects in low earth orbit poses a significant risk of collision with spacecraft or satellites, which could lead to damage or even mission failure, making space debris a crucial issue for space exploration. There have already been some collisions with space debris, one example is the collision of the functional Iridium 33 satellite with the defunct Cosmos 2251 satellite in 2009, which destroyed both satellites and generated further debris [1,2]. This example illustrates the necessity of space debris removal to avoid future fragmentation events that increase the number of debris objects in orbit. Space debris come from both natural and artificial sources. Natural debris includes micrometeoroids and fragments of small solar system bodies (such as asteroids or comets), while artificial debris results from defunct, damaged, or fragmented spacecraft, rocket bodies, or any other non-functional man-made objects [3]. According to NASA, more than 11,000 metric tons of space debris is present in Earth's orbit as shown in Fig. 1 [4]. Defunct spacecraft or other non-functional man-made objects have accumulated, and as a result, are prone to collide with other objects, which can cause more debris and could hypothetically result in a chain process known as the Kessler syndrome [5,6].

Several passive and active space debris removal techniques have been introduced to remove space debris. Passive debris methods include mitigation approaches such as drag sails [7]. Active methods require spacecraft to rendezvous with debris in order to remove them

* Corresponding author at: Astronautics and Robotics Laboratory (ASTRO Lab), Department of Earth and Space Science and Engineering, York University, 4700 Keele Street, Toronto, ON M3J 1P3, Canada.
E-mail addresses: mbazz@yorku.ca, mbazzocc@clarkson.edu (M.C.F. Bazzocchi).

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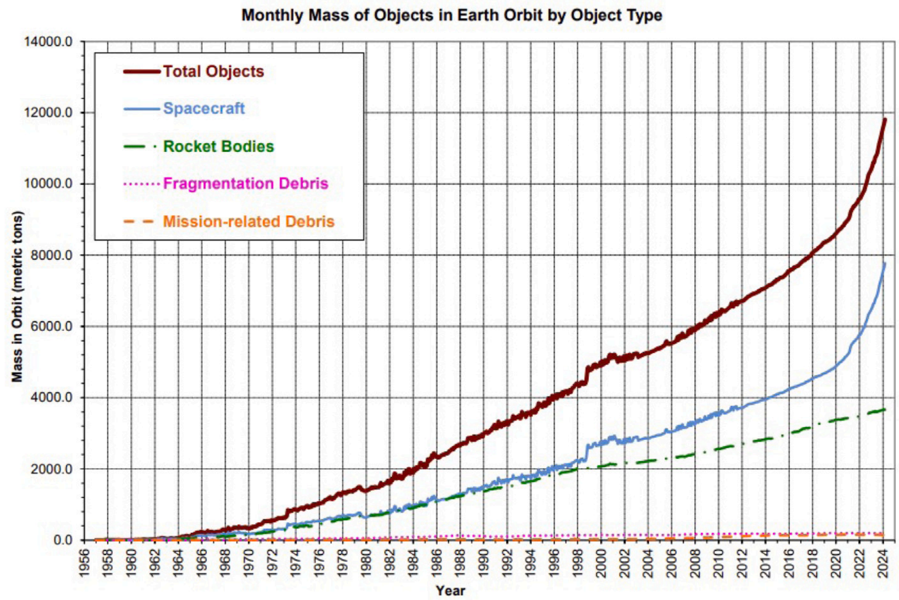

Fig. 1. Monthly mass of objects in Earth orbit cataloged by the U.S. Space Surveillance Network as of 9 June 2024 [4].

from orbit [8], and are categorized into contactless and contact methods. Contactless methods include the ion beam shepherd (IBS) [9,10], laser [11], electrostatic tractor [12], gravity tractor [13], and foam-based methods [14] and do not require physical contact with debris objects. In contrast, contact methods are categorized into rigid and flexible capturing methods that physically interact with debris objects for removal. Rigid capturing methods include tentacles [15], robotic arms [16], deorbiter CubeSats [17], and Sling-Sat [18]; whereas, flexible methods include nets [19], tethered grippers [20], and harpoons [21]. Rigid capturing methods have a risk of generating fragments because of their stiff composite behavior. On the other hand, in flexible capturing methods, systems often have the capability to capture the debris irrespective of its shape and size without generating fragments, but are challenging to control, and there is a risk that fast tumbling targets can break or evade flexible systems, *e.g.*, tearing a net [22]. However, some flexible systems, such as harpoon capture systems, have the capability to capture differently shaped targets and do not need a specific grasping point; but, there is a risk of generating fragments because of the necessary penetration forces exerted on the debris objects [23]. Therefore, researchers are actively proposing advanced removal techniques to address these issues and improve the viability of active space debris removal approaches.

In terrestrial applications that require dynamic capture of fragile, moving objects in unstructured environments with uncertainty in inertial parameters, soft or compliant mechanisms have rapidly emerged. The rapid development of such mechanisms for terrestrial applications has opened new opportunities to develop compliant capturing systems for space debris removal. Soft robots have the capability of substantial bending and deformation [24]. Additionally, they are ideal for handling unstructured and dynamic environments because of their compliance and adaptability [25]. Soft robotic grippers also have the capability to absorb energy during a collision with a target. Hence, these factors suggest that emerging soft gripper technologies should be investigated for space debris removal. Various materials and techniques have been used to develop soft grippers, *e.g.*, granular jamming [26], low melting point alloy [27], electrorheological materials [28], magnetorheological materials [29,30], shape memory materials [31,32], electroadhesive [33], and gecko-inspired adhesive [34]. While there are many challenges in adapting soft grippers for space applications, these designs are reviewed and discussed in this paper.

Regardless of the capture or grasping mechanism, estimating the inertial parameters of a space debris object is essential when using contact-based methods, such as robotic manipulators and tethered grippers, to determine the interaction dynamics. First, determining the grasping location on a debris object requires some knowledge of the target debris object's geometry and inertia. Then, once the target has been captured, the dynamics of the system will change, and, usually, the capturing spacecraft and debris object are treated as one system. Accurately determined inertial parameters are then useful for detumbling as well as deorbiting debris, particularly if the deorbiting mechanism, such as a thruster, requires precise directional control to be effective [35]. Inertial parameters are usually determined in three ways, *i.e.*, vision-based [36], momentum-based [37], and forced-based estimation [38]. Vision-based estimation is usually performed in the pre-capturing phase, while momentum and forced-based estimation are usually performed during or post-capture [39]. These estimation approaches vary depending on the available onboard hardware and the space debris removal method.

Several space debris removal techniques leverage robotic manipulators for performing estimation or grasping tasks. Generally, the spacecraft base and manipulator motion are coupled, so that movement of the manipulator can result in rotation or translation of the spacecraft base. Additionally, the space environment requires that any space debris removal method is able to respond to external disturbances and parameter uncertainty. As a result, the design and modeling of control systems for removal methods is necessary—particularly for systems that leverage manipulators for precise close proximity grasping [40]. Direct control methods are prominent in space applications, as they allow a user to operate and control communication, *e.g.*, a joystick was used by a human to control the Canadarm2 on the International Space Station to perform tasks. Applying the direct control mode for space debris removal is quite difficult because the stability of the direct control system may be compromised if the feedback signal fails to reach it in time due to the round-trip time delay (*i.e.*, the interval between transmitting a discrete signal and receiving any feedback) [41,42]. Virtual reality and mixed reality technologies are able to overcome time delay problems to some extent and can be promising technologies for space debris removal applications [43–45].

In this paper, a review of strategies in close-proximity operations for space debris removal, including inertial parameter estimation and control approaches, is presented, alongside emerging terrestrial soft

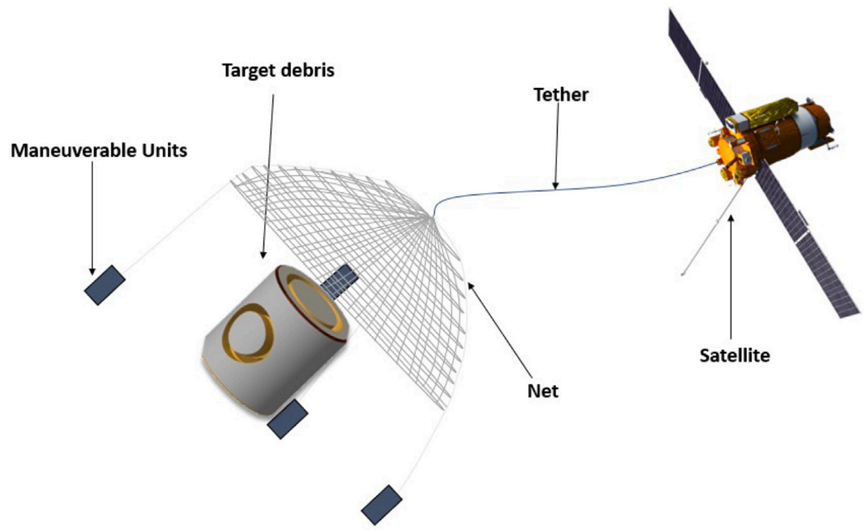

Fig. 2. Net-based method for removing space debris that includes maneuverable units attached to the satellite by a tether in order to capture the target, similar to [46].

robotics technologies that can potentially be adopted for space applications. The paper is organized as follows: Section 2 presents different methods for close-proximity space debris removal. The methods include tentacles, nets, harpoons, tethered grippers, robotic arms, and deorbiter satellites. Section 3 discusses different types of soft grippers that have been used to capture irregularly shaped objects in terrestrial applications. In order to capture, detumble, and deorbit space debris effectively, it is necessary to estimate inertial parameters of the target. The techniques used to estimate the inertial parameters are discussed in Section 4. Teleoperation, including discussions on virtual and mixed reality teleoperation, are presented in Section 5, with concluding remarks in Section 7.

2. Prominent active space debris removal methods

Various kinds of space debris removal techniques have been proposed, and as mentioned previously, can be mainly classified into active and passive approaches. Typically, passive debris removal methods, such as drag sails, can be included in the spacecraft design process in order to assist with deorbiting at the end of mission life. While this is important for mitigation efforts, for most current space debris, active removal methods are necessary to decrease the natural orbital decay timeline.

Active space debris removal methods consist of both contact and contactless methods. Contact methods are categorized into rigid methods (such as tentacles [15], robotic arms [16], deorbiter satellites [17], and Sling-Sat [18]) and flexible methods (such as tethered nets [19], tethered grippers [20], and tethered harpoons [21]). While contactless methods include ion beam shepherds (IBS) [9,10,47–49], laser-based approaches [50–52], electrostatic tractors [12], gravity tractors [13] and foam-based methods [14]. This review primarily focuses on contact-based methods for close-proximity operations in space debris removal. However, for comparative purposes, a brief review of contactless methods is also included. The risk of generating fragments is increased in rigid removal methods due to the stiff composite behavior during target contact and interactions. In flexible removal methods, the risk of generating fragments is reduced, but there are often additional challenges related to complicated deployment, capture, and combined system control that can be difficult to resolve. The following subsections present prominent active space debris removal methods, namely, nets, tethered grippers, harpoons, tentacles, robotic manipulators, deorbiting modules, laser-based methods, ion beam shepherd, electrodynamic tethers, solar sail-based methods, foam-based methods, Sling-Sat methods, and other unconventional methods.

2.1. Net-based methods

Net-based space debris removal methods consist of a group of approaches that seek to capture a debris object through envelopment with a net or mesh. A typical net capturing system consists of four flying corner masses, called bullets, which are connected to the net mouth [53,54], and facilitate the net expanding and wrapping around a target. The major advantage of net-based methods are that they do not need to estimate the inertial parameters of a target before capture [23]. However, capturing space debris using a net is challenging as the rotational and translational motion of the debris can alter the geometry of the net and, subsequently, cause the debris to escape from the net. Additionally, fast-rotating debris can also tear the net [22].

Researchers have developed different net-based models to capture space debris. For example, in [55], the dynamic characteristics of a tether-based net was examined during the initial deployment phase. The dynamics parameters included maximum net area, deployment time, traveling distance, and effective period. The tethered-net was modeled based on an absolute nodal coordinates formulation (ANCF) method and a mass–spring method for comparison. The result shows that an absolute nodal coordinates formulation model is effective for describing tethered-net dynamics. In [56], a lumped-parameter approach was used to model the net. The simulation was performed for deployment and capture dynamics. In [46], a contact dynamic model of the tethered net robot system and the target was introduced by using a mass–spring model. Moreover, super-twisting adaptive sliding mode control was also introduced to close the net completely and to mitigate the risk of the tether tearing (an example of a tethered net robot system is shown in Fig. 2). In [57,58], a maneuverable net system was introduced by replacing conventional flying weights with a maneuverable robot. The proposed system has the capability to maintain the shape of the net during capture.

Researchers have also investigated the capturing, post-capturing, and net closing mechanisms, *e.g.*, in [59], a relative velocity-based control scheme was modeled to detumble an object by controlling the motion of the chaser. The control method was able to reduce fuel consumption in the post-capture phase. In [60], a control strategy was introduced to detumble a tumbling target by tether tension to avoid collision between the target and the capturing spacecraft. In [61], a non-ideal case was discussed in which the target does not collide with the net center, which results in asymmetric net positioning. To counter this issue an integral adaptive super-twisting sliding mode controller was presented to close the net. In [62], an impulsive adaptive super-twisting sliding mode controller was introduced to close the net in a

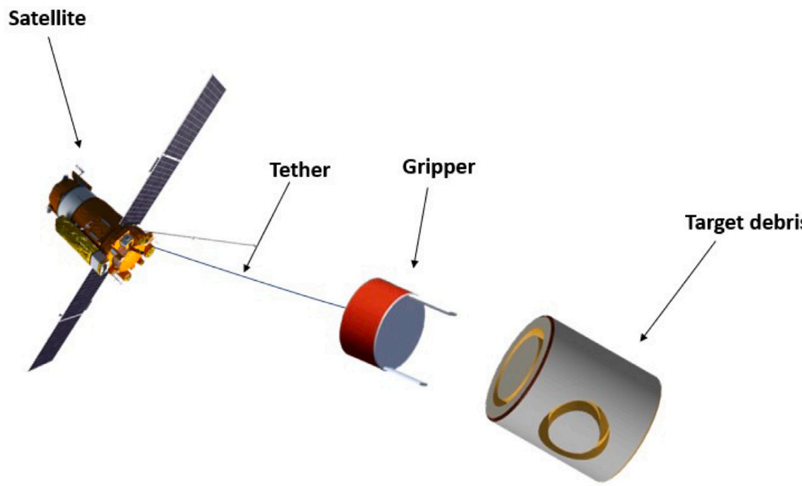

Fig. 3. The tethered gripper fired from the satellite to the target location, where it carries out grasping and detumbling operations, similar to [65].

shorter time frame for the same non-ideal case.

In [63], a mass–spring model was used to model the tether net space robot. A controller based on a sliding mode control law, combined with a nonhomogeneous disturbance observer, was used to close the net. The net remained closed and did not reopen after being closed. The proposed scheme did not address fast tumbling targets or objects with complex shapes. In [64], novel control laws to regulate the deployment and closure of the net were introduced. The deployment controller was designed to manage the tether length, while the capture controller employed a nonlinear proportional-derivative (PD) tension control law. The proposed closing mechanism showed promise, but further work was suggested to account for debris rotation, sensor noise, and parameter uncertainty.

In [66], a novel closing mechanism was proposed, where split masses were used to drive the closing thread, effectively pulling the net mouth closed. Both the tether-net and the thread-ring sliding joint were modeled using the mass–spring-damper method. The split closing mechanism enabled the tether-net to reliably envelop the target in a short period of time.

In [22], the net's dynamics were modeled using the Kelvin–Voigt method, while the debris dynamics—both translational and rotational—were simulated by incorporating microgravity, perturbative, and contact forces. A sliding mode control-based scheme was also proposed to actively tow debris using a flexible net. The findings demonstrated that the control scheme was very effective at capturing debris as well as the debris was fully encapsulated, allowing it to be moved along the designated trajectory. The study also demonstrated that debris rotating at 6.28 rad/s can be captured by the flexible net. Similarly, in [67], the tether tension was also modeled using the Kelvin–Voigt model, and the net was modeled using a mass–spring system. A dynamic closing point strategy was proposed to determine the final position where the four maneuvering units converge. The results showed that the dynamic point strategy was effective in capturing both stationary and tumbling targets, while also being fuel-efficient.

Net-based space debris removal methods are beneficial since they: (i) do not require any specific grasping point of the target, (ii) can capture most types of debris, (iii) can reduce the risk of generating fragments, and (iv) are less sensitive to the inertial parameters of the target. On the other hand, net-based methods have several challenges related to the control of fast tumbling targets [22] and control in the case of asymmetric net positioning [61]. They also have a risk of oscillations [23] and net tearing [22] during target capture.

2.2. *Tethered gripper-based methods*

The tethered gripper concept was first proposed by the European Space Agency (ESA) RObotic GEostationary orbit Restorer (ROGER) study [65]. The structure of the tethered gripper is comprised of a three-finger gripper and a tether that connects the gripper to the satellite. The gripper is launched from a satellite towards the target in order to grasp, and subsequently detumble or deorbit the target. An example of a tethered gripper system is shown in Fig. 3. Many researchers have proposed motion planning and control models for capturing and post-capturing phases, *i.e.*, to track, rendezvous, grasp, and/or control non-cooperative moving object [68–71]. For example, in [72], a visual perception system for a tethered gripper system was introduced. The system was based on the pyramid Kanade-Lucas-Tomasi matching algorithm, a speeded-up robust features algorithm, and a greedy snake algorithm. In [73], a novel localization algorithm was introduced to identify the region of interest of targets in an image before determining their features. The method was based on the improved histogram of oriented gradients descriptor and a support vector machine, and showed robustness against environmental effects, such as noise and luminance.

The collision between the target and the gripper can destabilize the system and entangle the tether [74]. Thruster control can be utilized to stabilize the combined system, but it can lead to high fuel consumption. To counter these issues, an attitude coordinated control strategy based on a genetic algorithm was introduced in [74]. However, the tether was taken as massless in this case. In [71], an optimal coordinated controller was introduced based on an hp-adaptive pseudo-spectral method and a proportional derivative (PD) controller that significantly reduced fuel usage during the approach phase while including the mass of the tether.

Generally, it has been assumed that the tethered gripper uses a camera to estimate the attitude and position of the target. However, to estimate the parameters the target must be in the field of view of the camera, which can be challenging in the approaching phase. To address this challenge, a non-singular terminal sliding mode method was introduced in [68] to develop an position and attitude coordinated controller, and a Gaussian pseudospectral motion planning model was utilized to attain optimal trajectory for the approaching task. For the post-capture phase, a control model was introduced in [69] for attaining attitude stabilization and the Gauss pseudospectral method was also used to mitigate post-capture issues. In [70], a coordinated robust adaptive backstepping control method was introduced for post-capture stabilization and to mitigate the thruster's saturation issues.

The tethered gripper has the potential to remove space debris. The advantage of this method is that the flexible tether can avoid

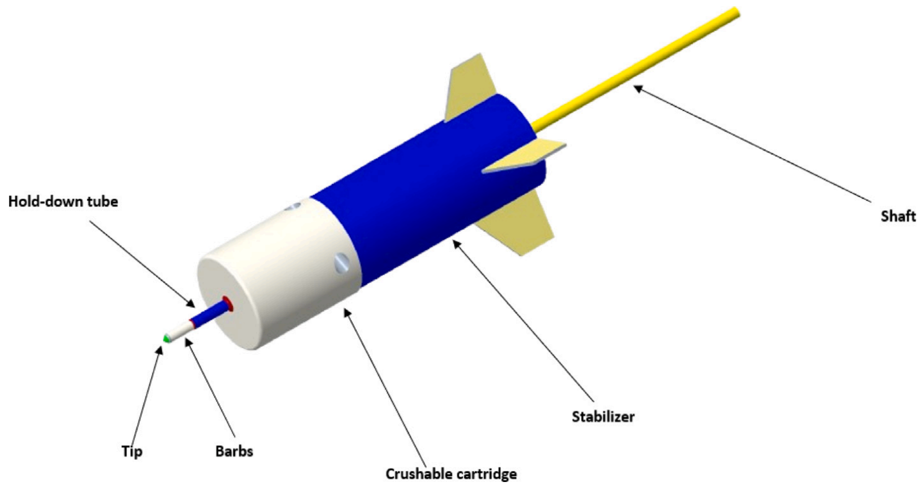

Fig. 4. Example of a harpoon projectile.
Source: Concept adapted from [21].

rigid collisions with the debris [75,76], while also enabling efficient capture operation time [23]. Similar to net-based approaches, tethered gripper-based space debris removal methods tend to have difficulty with capturing fast tumbling targets. However, unlike net-based approaches, this is primarily due to the requirement of needing to reach a specific grasp point on the target. Additionally, due to its flexibility and variation in the tether length, tethered gripper methods can have complicated deployment, rendezvous, and control phases during capture, as well as challenges with twisting and collision during towing operations [77].

2.3. Harpoon-based methods

The structure of harpoon-based methods typically constitute a tether, a firing system, and a projectile that includes a set of barbs and a crushable section. A capturing spacecraft is connected to a projectile via a tether, and launches the projectile or harpoon towards a debris object for capture. The crushable section on the harpoon absorbs energy on impact, while the barbs are used to affix the projectile to the target [21]. Once the harpoon is attached to the target, the capturing satellite applies forces and torques via the tether to detumble or deorbit the target. Fig. 4 presents an overview of the harpoon mechanism. In the past, researchers have studied the details of the harpoon mechanism as well as the detumbling of targets via the tethered system. For example, in [78], metal harpoons were examined with varying tip geometries (namely, conical, spherical, flat, and double-bladed) and penetrated the target at different angles, *i.e.*, 0°, 30°, and 45°. In [79], two harpoon designs were introduced having a flat and conical head for projectiles that could provide the greater perforation.

To detumble a non-cooperative target, a harpoon with a low-thrust device was introduced in [80]. When the servicing satellite approaches the target, it first uses its visual system to estimate the target's motion before selecting an optimal location on the target for the harpoon to strike. The servicing satellite then performs movements to align with the target's attitude before firing the device into the optimal location of the target and forming a combined system between the target and the harpoon with the low-thrust device. After attachment, the electric propulsion system of the device connected to the harpoon reduces the angular velocity of the combined system. In [81], three stages of space debris removal using a harpoon mechanism were investigated. These stages are capture, tether deployment, and towing. An algorithm was also developed to determine the optimal parameters for the capture, deployment, and towing phases.

The harpoon has the capability to mitigate space debris of irregular shapes because it does not require a grasping point with specific geometry and can capture various types of space debris. However, during the approach phase there is a chance that the harpoon does not strike or maintain a hold on the debris object, particularly since there may be attitude determination measurement errors and delays between target acquisition and harpoon launch. In general, further experimentation is required to know the reliability and practicality of harpoon-based mechanisms. There is also a high risk of generating fragments because the harpoon is required to physically penetrate the target debris object, which makes harpoons less suitable for broader space debris mitigation approaches.

2.4. Tentacles

A unique concept for space debris removal, namely, tentacle-based clasping mechanisms, was investigated as part of an ESA study for the deorbiting of the nonoperational spacecraft, ENVISAT [15]. In particular, several configurations of clasping mechanisms were proposed that incorporated flight-proven mechanisms, such as booms, capture mechanisms, spring hinges, dampers, latches, end stops, release mechanisms, rotary actuators, and active damping linear actuators [15]. Fig. 5 presents an example of a tentacle-based capture mechanism with four booms. Nine different configurations were investigated, with the most promising concepts including a combination of either two or four tentacles (or booms). For example, the configuration with two tentacles, had two booms each with two rotational degrees of freedom. The two booms extend the length of tentacle (double than the chaser length) using a combination rotary joints, rotary actuators, and linear actuators, with locking on to the target supported through the use of a leaf spring. While this concept could be extended to four tentacles, in general, the four tentacle configurations did not require linear deployment. For example, one of the leading four tentacle configurations utilized rotary actuators, booms, and leaf springs for each tentacle, which were stowed using two hold-down and release mechanisms prior to deployment for target capture. The four tentacle configuration was driven by rotary actuators that facilitated capturing the target, but were limited by the length of the boom. Generally, these tentacle-based configurations were considered practical due to their low cost and high reliability through the use of all simple, flight-proven components [15]. However, there has been very limited work extending the studies on tentacle-based mechanisms, with more work focused on a similar type of capture mechanism, namely, robotic arms, which are discussed in the following subsection.

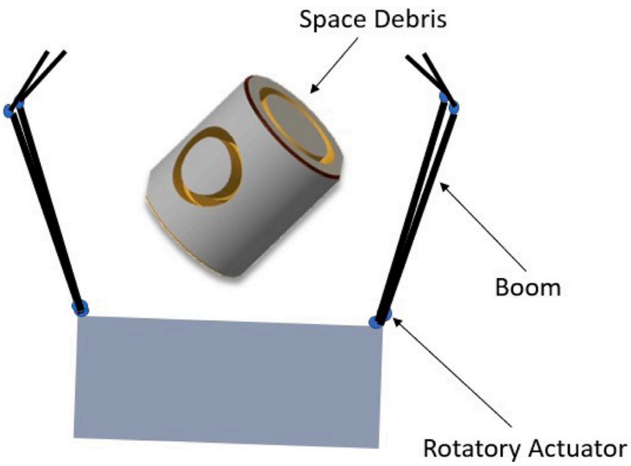

Fig. 5. Example of a tentacle-based capture mechanism.
Source: Concept adapted from [15].

Fig. 6. Space robotic arm attached to a spacecraft, both stowed and partially deployed [83].

2.5. Robotic arm with hard gripper

Another prominent method to mitigate space debris is through the use of space manipulators. Space manipulators are comprised of a spacecraft base with at least one robotic manipulator, and are often categorized as free-flying and free-floating. For free-flying manipulators, the base is actively controlled (*i.e.*, controlled position and attitude); whereas, free-floating manipulators do not maintain positional or attitude control of the base during operations, often to conserve fuel [82]. An example of a space manipulator [83] is illustrated in Fig. 6.

Capturing space debris using a space manipulator usually involves three phases: pre-capturing, capturing, and post-capturing [84]. In the first phase the manipulator has to proceed in the direction of the intended grabbing position to capture the target. The second phase deals with capturing the target. The third stage is called the post-capturing phase in which the servicing system is stabilized. Further it is important to note that the dynamics of a space manipulator can be complicated because the manipulator and spacecraft are tightly linked with each other, and can often be of a similar mass (or less than the mass) of the target being captured. Any movement either rotational or translation by any of these will create the disturbance and will affect the whole system [85]. In this subsection, recent methods used for space manipulator trajectory planning and control are briefly discussed—with more detailed reviews on the topic available in [86, 87].

In [88], a trajectory planning scheme was introduced for multi-targets based on proximal policy optimization (PPO) algorithm for a free-floating space robot manipulator. The proposed strategy was efficient and was validated on different cases, which included external disturbances at joints, different masses of the base, and single joint failure. In [89], an acceleration-level trajectory planning method was introduced for dual arm space manipulator while considering some joint physical constraints. In [90], the Deep Deterministic Policy Gradients (DDPG) algorithm was used to develop a motion planning strategy to mitigate the complex constrained motion planning problem of free-floating dual arm space manipulators. In [91], a trajectory planning was developed based on particle swarm optimization and kinematics equations for a kinematically redundant free-floating space manipulator. In [92], an improved hybrid particle swarm optimization was introduced for a redundant manipulator to mitigate the trajectory planning issue while keeping the base attitude disturbance to a minimum. In [93], the nonholonomic property of a space manipulator was analyzed and parameterized the joint trajectory. After that planning problem was taken as an optimization problem and resolved by employing a genetic algorithm and quantum genetic algorithm. In [94], a novel coordinated trajectory planning method was introduced for a free-floating dual manipulator to avoid obstacles during maneuvering and capturing of a target. In this method the optimal trajectory problem was taken as an optimization problem and then particle swarm optimization (PSO) was employed to optimize the trajectory of the space robot. Further, to address obstacle avoidance while capturing a tumbling target, a DDPG-based trajectory planning and control strategy was developed in [95] for both free-flying and free-floating space manipulators.

Various control models have been developed to ensure effective trajectory tracking during the approach (pre-capture) phase, *e.g.*, in [96], a control method was introduced for trajectory planning based on convex optimization for a kinematically redundant manipulator to mitigate the base attitude disturbance. In [40], a control method based on adaptive fuzzy neural network was introduced for trajectory tracking control of free-flying space manipulator while considering parametric uncertainties and external disturbances simultaneously. The output constraints and input nonlinearities were also taken into account. In [85], an adaptive controller was designed for trajectory tracking control of a free-flying space manipulator while considering various factors, such as actuator saturation, disturbances, and parametric uncertainties.

Capturing the target is the second phase of the capturing process. When the manipulator approaches the target for capture, a dynamic interaction between the manipulator and the target will take place. Due to the dynamic interaction, the base of the space manipulator may be impacted, affecting system stability or damaging the target. Safe contact is required in order to capture a target.

Many control methods have been introduced for capturing a target, *e.g.*, a two-phase capturing process based on an improved damping control method was introduced in [97]. The capturing process included a collision phase to create a force-closure grasp configuration and to ensure stable contact between the gripper and target, while the locking phase enabled the gripper to lock onto the graspable structure. In [98], a position-based impedance control method was developed to capture a non-cooperative target through gentle contact between the end-effector and the target. Results showed that the developed control method was suitable for capturing a tumbling target. In [99], a control strategy was formulated by the use of joint compliance control and incorporating buffers into the end-effector for direct contact with the target. In [100], the kinematics and dynamics equations were derived using a quasi-coordinate Lagrangian for a free-flying dual-arm manipulator and then the use of an impedance control system to capture a tumbling target was investigated. In [101], a novel control scheme was developed by integrating impedance and sliding mode control for capturing a non-cooperative target while taking force constraints into account. In [102], a novel control system was introduced by integrating impedance control with proportional-derivative control to maintain contact between the target and the manipulator before capturing.

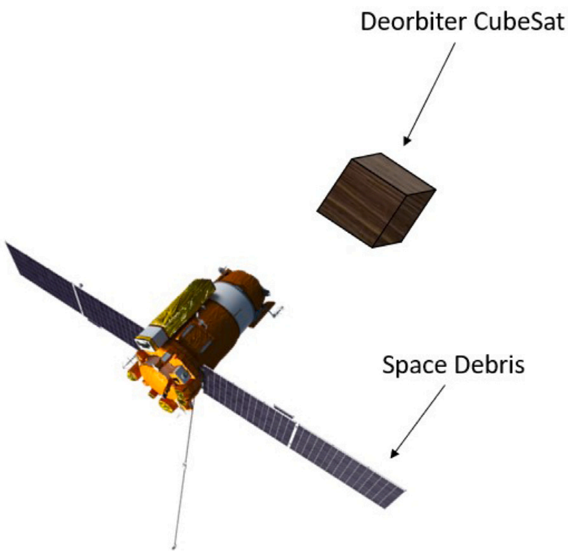

Fig. 7. Example of a deorbiter CubeSat.
Source: Concept adapted from [17].

There have been a vast number of studies focused on the use of robotic arms equipped with hard grippers for space debris capture, but their rigid behavior has the potential to generate fragments during the capturing phase, and, hence, increase the risk of further space debris. A space manipulator with a soft gripper may offer a promising solution for mitigating space debris due to its ability to dissipate impulse upon contact and, thus, reduce the potential of generating fragments during capture. The topic of soft grippers is discussed in further detail in Section 3.

2.6. Deorbiting module-based space debris removal

Several researchers have explored the concept of using nanosatellites or CubeSats to deorbit space debris. For example, in [103], the design of a multi-satellite mission was introduced to mitigate space debris. The design mission was comprised of six nanosatellites and a minisatellite referred to as the mothership. The mothership estimated the attitude state of the target and viable docking position for the nanosatellites. The nanosatellites performed docking with the target and used thrusters to detumble the target. After that the nanosatellite performs docking with the debris for deorbiting. A similar design was proposed in [104], in which spacecraft placed remover kits onto the target and deorbiting was performed by two alternatives *i.e.*, electrodynamic tether or electric propulsion. In [17], a mission concept was introduced based on a single CubeSat referred to as a deorbiter CubeSat. The mothership utilized orbital and attitude control actuators to place the CubeSat onto the debris and then the CubeSat used a low-thrust propulsion system for detumbling and deorbiting the target. In this case, the mothership does not need to perform a deorbiting maneuver. Fig. 7 depicts the single deorbiter CubeSat concept.

CubeSat methods have the capability to remove large and small space debris but have a complicated rendezvous phase because the mothership needs to perform a maneuver first in order to align itself with the space debris, and then the CubeSat has to perform a rendezvous with the target. In the case of fast tumbling targets, there is a chance that the debris will escape during the rendezvous phase. Furthermore, there is a chance that the CubeSat will be damaged during attachment (or collision) with the space debris object. However, this approach has the potential to remove multiple large debris objects through a mothership-based approach to debris remediation.

2.7. Laser-based methods

When targeting space debris, space-based laser systems are often operated in two different modes, namely, direct ablation mode and ablation back-jet mode, depending on the debris type. The direct ablation mode is often applied to small debris particles, whereby the laser irradiates the surface of the debris until the material ablates or vaporizes. In contrast, the ablation back-jet mode strategically ablates a spot on the debris surface to create a “jet” of gas that creates a reaction force (usually in the opposing direction of motion). The ablation back-jet mode is often applied to larger debris over time to slowly reduce their orbital altitude until deorbitation [51]. The concept of using space-based laser systems for debris removal has been studied for several decades. For example, in [50], the concept of employing high-power laser systems for space debris removal was introduced. The study proposed the use of an orbital vehicle equipped with a laser to alter the trajectory of debris, and, thereby avoid potential collision. By employing thrust impulses, this system would be able to direct the debris for re-entry into Earth’s atmosphere.

In [51], a space-based laser system was introduced to alter the trajectory of the debris through the upper atmosphere. The study showed that the optimal repetition frequency for the laser system was 100 Hz; frequencies lower than this were suggested to be insufficient for debris mitigation or elimination. While higher repetition frequencies could be used to reduce elimination time, but could result in thermal issues leading to higher costs. Additionally, the study indicated that the angle between the debris orbit and the laser orbit should be less than 30°, as a greater angle decreased the efficiency of debris elimination.

In [105], a fiber-based International Coherent Amplification Network (ICAN) laser architecture was proposed for tracking and deorbiting purposes, powered by a solar array. This architecture included three operational modes: scanning mode, tracking mode, and shooting mode. Analytical calculations indicated that the system offered high efficiency, precise phase array control, and rapid pulse repetition, enabling the deorbiting of hyper-velocity debris through laser ablation in a single instant.

In [106], a hybrid ground- and space-based laser system was proposed. Firstly, a laser ablation impulse coupling model was established, followed by a momentum transfer model derived from an analysis of orbital transfer. The simulation results demonstrated that the proposed method was capable of removing a target space debris object using 1,553 laser pulses at an altitude of 800 km within a single pass.

In [107], the mechanisms of laser ablation are examined, including the heating, melting, and evaporation of the target, along with the formation of a plume and plasma. The study also investigated the influence of key parameters on laser ablation such as laser irradiance, wavelength, and pulse width. The study considered aluminum as the target material. Simulation results showed that laser ablation was strongly influenced by incident laser irradiance and pulse width, while wavelength has a lesser effect compared to the other two factors. The study also observed that splitting a long-duration laser ablation into two short-duration pulses can enhance the impulse density on the target, as well as the corresponding impulse coupling coefficient. However, the time interval between the two pulses should be small.

In [108], the momentum of various shaped debris was analyzed while incorporating thermal constraints in the laser irradiation configuration. In this study, the ground-based laser setup (see Fig. 8) was defined with a pulse energy of 100 kJ, a wavelength of 1030 nm, and a pulse repetition rate of less than 10 Hz in order to prevent debris melting. For rocket bodies, the repetition rates should be kept below than 10 Hz. The study further determined that debris ranging from 10 to 40 cm in size can typically be deorbited within 100 to 400 station passes and head-on irradiation. However, for debris larger than 2 meters, more than 1,000 passes are usually required. They also found that 3,000–30,000 passes may be required for some cases, which was not considered to be a realistic or efficient approach for debris

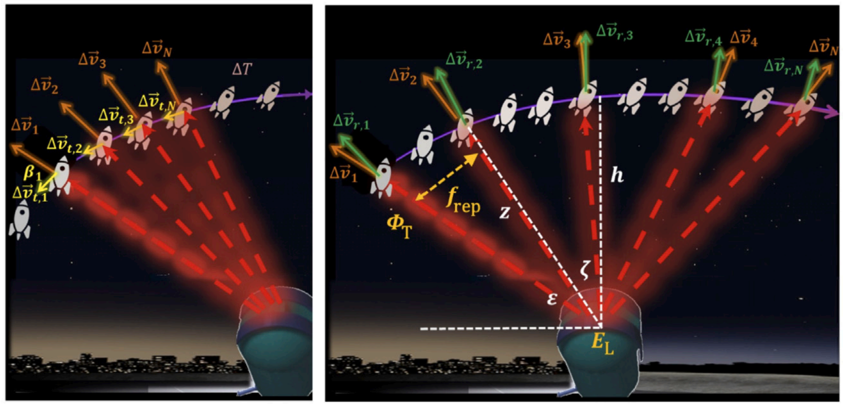

Fig. 8. Design of a high-energy laser ground station that repetitively pulses lasers at space debris to lower its perigee: (a) through head-on momentum transfer and (b) through outward momentum transfer [108].

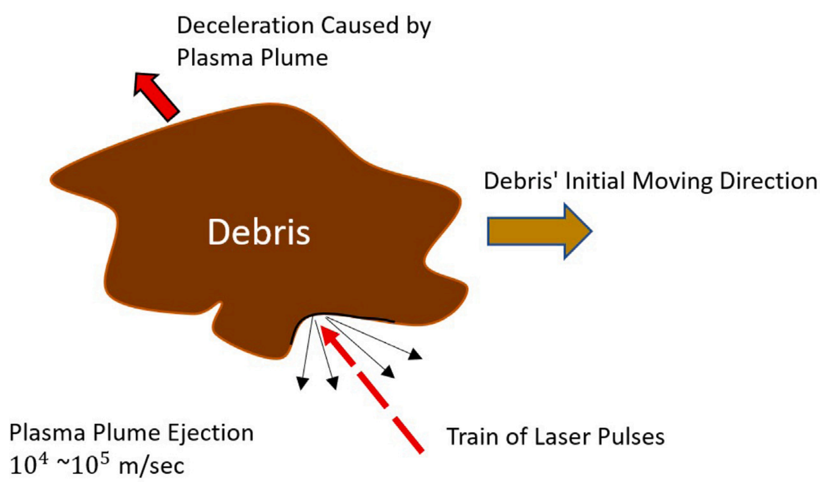

Fig. 9. Sequence of laser pulses striking space debris, causing ablation of the material [109].

removal.

In [109], an assessment study explored the power requirements for eliminating space debris, specifically examining the use of short-wavelength lasers to vaporize debris. It explored two laser removal cases: (1) laser vaporization, and (2) laser ablation. In both cases, the laser could be powered by solar energy. The study also revealed that the laser vaporization method required more energy than the laser ablation technique, which made laser ablation the preferred approach. An example of space debris being ablated after being hit by a train of laser pulses is shown in Fig. 9.

Laser-based space debris methods are contactless space debris removal methods that present a promising solution for deorbiting or vaporizing targets, despite challenges related to ejecta plume degradation [110]. However, for larger debris targets there remains a high risk of debris breakup, generation of particulate, and long duration reentry time frames. Laser methods also tend to have difficulty ablating material from fast tumbling targets, since the laser may not be able to focus on a spot for sufficient time to result in ablation [110].

2.8. Ion beam shepherd methods

The ion beam shepherd satellite (IBS) concept [9] features a propulsion system that uses a beam of quasi-neutral plasma to propel a target, harnessing the momentum of the plasma ions to generate thrust. In [9], the design of the ion beam shepherd method was optimized to minimize the total mass of the IBS required for debris deorbiting by deriving the optimal propellant exhaust velocity. The following assumptions were taken into account in a preliminary assessment of deorbiting using the IBS: (i) the space debris was in a circular orbit, (ii) the beam of quasi-neutral plasma exerted a constant force that was always tangential to the orbit of the debris, and (iii) the orbit evolved in a quasi-circular manner throughout the spiral transfer.

In [48], the atmospheric effect on the attitude motion of the space debris caused by the ion beam shepherd in low Earth orbit was analyzed. The equations of motion for the space debris considered planar motion under the influence of various perturbations, including those resulting from gravitational and aerodynamic forces, and the ion beam impinging the debris. The study used the Cosmos 3M rocket stage as

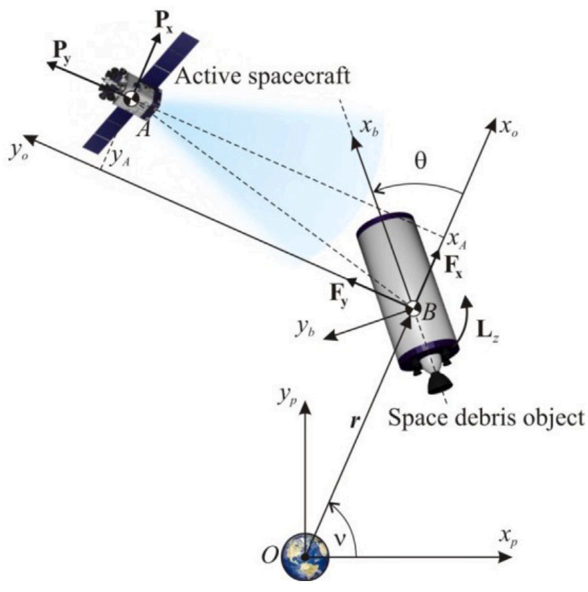

Fig. 10. Schematic of the ion beam shepherd mechanical system, consisting of an active spacecraft and a space debris object. The spacecraft uses an ion beam to exert force on the debris, guiding it to a desired orbit or trajectory [111].

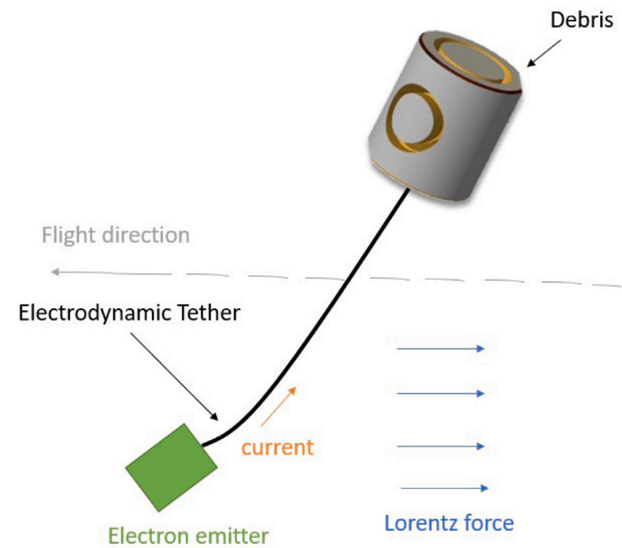

Fig. 11. The electrodynamic tether concept.
Source: Adapted from [112].

an example of a space debris object to remove from a circular orbit at a 500 km altitude. Newton impact theory was used to calculate the dimensionless aerodynamic coefficients. Results showed that the time for an object to descend from orbit was reduced by the increased effect of the atmosphere. The study also highlighted that cylindrical space debris, with its center of mass aligned along the axis of symmetry, experienced phase portrait deformation due to atmospheric influence, though this did not result in any qualitative changes to the dynamics. Furthermore, the study revealed that the average ion beam force over the oscillation period was significantly influenced by the amplitude of space debris oscillations, which consequently influenced the overall descent time.

In [111], the impact of gravitational and ion beam forces and torques on the attitude motion of a space debris were studied. Lagrange formalism was used to formulate the mathematical model of the attitude motion. The study considered cylindrical space debris having undisturbed attitude motion and determined a suitable orientation of the space debris to exert the deorbiting thrust. An engine thrust control law is also devised in order to transfer the debris in the required angular motion mode. A depiction of the ion beam shepherd considered in this study is shown in Fig. 10.

In [49], the use of multiple ion beams for space debris removal was analyzed. The use of multiple ion beams produced a stronger ion beam force on the target. Two control schemes were used in this study: (1) relay control, which involves activating and deactivating the thruster; and (2) control of the ion beam axis direction for one of the thrusters. As expected, the results revealed that multiple thrusters reduced the descent time.

As previously discussed, the ion beam shepherd method is a contactless space debris removal method that uses a collimated ion beam to deorbit a target. This has the advantage of being capable of exerting a deorbiting force on debris without the inherent challenges associated with contact-based methods. However, one of the disadvantages is that it usually requires a secondary ion beam thruster to exert a counteracting force allowing the IBS to maintain a constant distant from the debris object. Additionally, given that the ion beam diverges with distance, depending on the debris size, maintaining an appropriate relative distance to ensure force is applied without too much loss can be another challenge. Lastly, although inherently a long duration deorbiting strategy, in order to apply a sufficient amount of force to enable timely deorbiting of large objects or where significant orbital change is required, multiple thrusters and large amounts of fuel may be required.

2.9. Electrodynamic tethers

Electrodynamic tethers are another promising method for removing space debris without the need for fuel. The electrodynamic tether method operates by generating Lorentz forces as the tether travels through Earth's magnetic field. The electrodynamic tether method has been widely explored by researchers for debris removal. For example, in [112], a strategy for removing 100 large debris pieces in densely populated regions, such as Sun-Synchronous Orbit (SSO) at altitudes between 900–1000 km with an inclination of 83 degrees, as well as altitudes between 1400–1500 km with inclinations of 52, 74, or 83 degrees. The study also proposed the use of a small piggyback-launched satellite for space debris removal, along with a dedicated satellite designed to remove debris. An electrodynamic tether (EDT) was considered ideal for deorbiting, as it required minimal propellant and low electrical power. Once the electrodynamic tether attaches to the debris, it causes the altitude to decrease due to the thrust generated by the tether. The study found that a tether with a length of 5–10 km can deorbit a large debris object from a populated orbit within one year. The concept of electrodynamic tether considered in this study is shown in Fig. 11.

In [113], the study examined the use of a micro-satellite system for space debris removal and evaluated the potential of electrodynamic tether (EDT) technology as an efficient system for orbital transfers. The mission detailed a strategy for measuring the motion of the target during rendezvous, determining the final approach by maneuvering around it for capture, and utilizing an extendable robotic arm equipped for the capture task. This arm extended an EDT anchored at its base. A small EDT package provided a potential solution for lowering the orbits of objects, effectively reducing the altitude of space debris. The study also provided insights into the prototypes of the EDT package that are currently in development.

In [114], the potential of electrodynamic tether (EDT) technology as an efficient system for orbital transfers was analyzed. EDT packages that were currently in development and comprised of conductive tethers and field emitter cathodes (FECs) using carbon nanotubes were examined. The FECs were made from aluminum wires and carbon fibers, designed to withstand severing from debris collisions. These FECs were preferred for their low power consumption without a warming-up time. Simulations were conducted to analyze various aspects, including available electric currents, deployment dynamics, orbital dynamics, and tether stability. The tether's flexibility, along with environmental factors, such as plasma density and geomagnetic fields, are accounted for by modeling it as a lumped mass. The results showed that the EDT system can deorbit the debris within the specified time frame, provided the tether survived potential severing from collisions with small debris.

In [115], the study examined the structural characteristics of electrodynamic tape tethers. Tape-shaped tethers offer several advantages, including their large width, which makes them more resistant to collisions with small space debris, and their large surface area, which facilitates the collection of a significant number of electrons from the surrounding space plasma, which improves debris removal. Large-scale hypervelocity impact experiments were conducted to investigate the relationship between the structural geometries of tape tethers and the impact holes created by debris collisions. The research established severing criteria for tape tethers, which determine whether these tethers will be severed upon colliding with small debris. Additionally, the study examined the correlation of survivability of the tethers with various tape dimensions, illustrating how this survivability varies with changes in size. The study revealed that the thickness and cross-sectional area of the tape are critical factors in establishing the structural design of such tethers. Survivability is influenced by the tensile force, thickness, and cross-sectional area, with smaller thicknesses improving survivability when the tensile force is low.

In addition to concepts for space debris removal, electrodynamic tethers are often considered as potentially proactive deorbiting strategies for satellites at the end of their mission life. The electrodynamic tether shows promise for mitigating space debris, with the key advantage of not requiring a propulsion system. Additionally, the time required to deorbit space debris can be relatively fast [116]. However, the flexibility and variation in tether length can complicate deployment and collisions with small debris can result in tether severing. Increasing the tether length may also lead to oscillations, while high-velocity debris can affect the tether's stability and impact, potentially damaging the tether. For a more in depth review of electrodynamic tether projects and missions that have been proposed for space debris removal, refer to [117,118].

2.10. Solar sail-based methods

The solar sail is another method that leverages the external environment to remove space debris. It generates thrust by harnessing solar radiation pressure. The sail can be deployed by spacecraft via tethered towing or a stiff grip and requires a large surface area to generate thrust due to the low solar radiation pressure. The solar sail concept is shown in Fig. 12. This approach is particularly effective for non-functioning satellites where the solar sail control system remains operational, but there is insufficient propellant for reentry. Many researchers have explored the solar sail method for debris removal, *e.g.*, in [119], a 6U CubeSat named "TugSat" is proposed, with dimensions of 30 × 20 × 10 cm. The CubeSat was designed to deorbit space debris in geosynchronous equatorial orbit using a sail-propelled method controlled by a nonlinear controller, providing sufficient delta-V for the maneuver. The nonlinear controller based on optimized vector geometries and Gaussian variation of parameters (VOPs) equations, produced sail orientations capable of tracking the desired orbital element values—such as semimajor axis, eccentricity, inclination, and longitude—enabling effective deorbiting of the debris. Monte Carlo simulations were employed to validate the effectiveness of these sail orientations.

A solar sailing satellite concept was presented in [121] for the purpose of deorbiting large debris to a graveyard orbit above the geostationary orbit. The study developed an optimized analytical solution utilizing Lyapunov control theory, enabling complex planetocentric sail maneuvering. It has been shown to be robust against higher-order gravitational perturbations and third-body effects from neighboring celestial bodies. Additionally, using particle swarm optimization (PSO) to optimize design parameters, the feasible deorbit times were reduced by more than 50%.

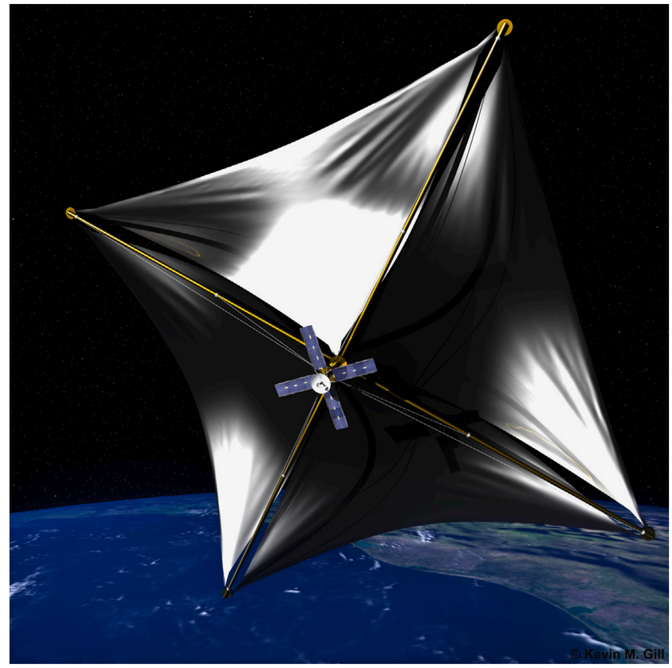

Fig. 12. Solar sail concept [120].

In [122], the mitigation of Earth orbit debris was explored, taking into account the primary perturbations affecting a solar sail. These perturbations included the Earth's oblateness, the gravitational influences of the Moon and Sun, and solar radiation pressure. The research leveraged the solar sail to increase the eccentricity and inclination of space debris in geostationary orbit. The Sun served as a propulsion system, providing a clean energy source, while the interactions between the solar sail and the debris were also considered. The single averaged model was used to derive the solar radiation pressure equation up to the second order.

Solar sails have the potential to remove space debris and offer the advantage of not requiring external fuel or power. However, the process is slow, and controlling the sail can be challenging. The angle between the sail's plane and the direction of sunlight influences the magnitude and direction of the force produced by the solar sail. This dependency limits the effectiveness of solar sails for deorbiting debris in those orbits where the plane is perpendicular to the Sun's direction [8].

2.11. Foam-based method

An innovative approach to mitigate space debris was introduced in [14,123], utilizing the distinctive properties of foams as a drag augmentation mechanism (example shown in Fig. 13). This strategy aimed to increase the debris' area-to-mass ratio, thereby amplifying atmospheric drag and promoting natural reentry from low Earth orbit. The study specifically considered polyurethane foams due to their high expansion factor and flexibility. Key characteristics of the foam included: (1) its sticky nature, allowing the debris and foam to form a cohesive system; (2) its ability to expand and polymerize when exposed to vacuum conditions; (3) a final expansion phase that achieved a high expansion factor with low density; and (4) its resistance to rapid degradation during atmospheric reentry. A platform equipped with an

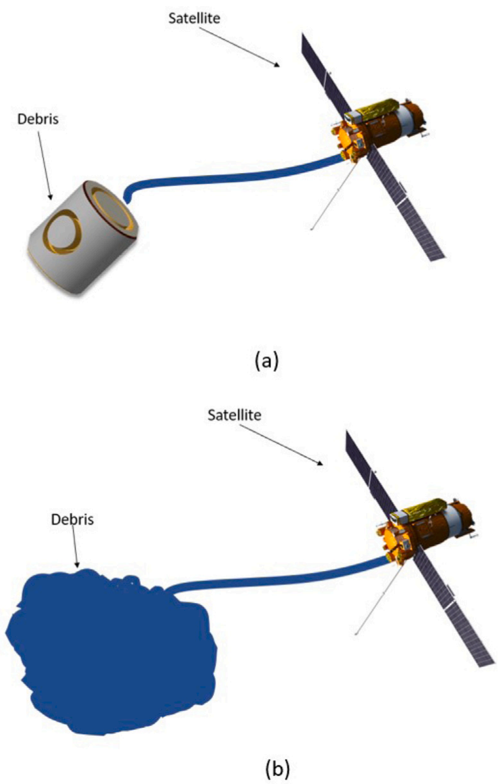

Fig. 13. Example of a foam-based method: (a) before the foaming process, the satellite approaches the debris; (b) after the foaming process with the debris enveloped in foam. *Source:* Concept adapted from [8].

electric propulsion system was designed to carry and deploy the foam. The proposed approach eliminated the need for docking systems and was capable of efficiently handling tumbling debris.

In [124], a momentum exchange method for space debris removal was proposed. This approach involved encasing debris with foam balls to increase its area-to-mass ratio, thereby enhancing atmospheric drag, resulting in deceleration and deorbiting. This paper also investigated the combination of this system with electric propulsion, which is responsible for delivering the foam to the debris. The study revealed that this foam-based method could deorbit more than 1 ton of debris annually.

In [125], the potential of polyurethane foam for deorbiting space debris was investigated. The foam was produced through a chemical reaction between two liquids, with adhesion tests conducted on aluminum (representing the debris). The study outlined two mission types: (1) controlled removal, and (2) uncontrolled removal. In the controlled removal scenario, the reaction between two components produced a high-density, medium-expanded foam. This rigid foam was used to form a strong connection between the satellite and the debris. The method leveraged the satellite's propulsion system to enable faster execution. In the uncontrolled removal scenario, a low-density, highly expanded, spongy foam was generated that enveloped the debris. This approach increased the area-to-mass ratio of the debris, enhancing atmospheric drag and promoting reentry.

The foam-based method is a relatively new approach that does not require a docking system. It enables the removal of multiple debris objects in a single mission by using an electric propulsion system to target and eliminate them one after another. Another advantage of the foam-based method is that the foam mass can be adjusted according to the type of debris, and the foam ball can be customized to achieve the desired deorbiting time. For debris weighing over 1 ton, the required foam mass may surpass the mass of the debris itself, rendering this method ineffective [14].

2.12. Sling-Sat method

The Space Sweeper with Sling-Sat (4S) was a mission proposed in [18] to mitigate space debris by catching debris objects with a spinning spacecraft and slinging them into a trajectory that would result in rapid deorbiting. The space sweeper leverages the momentum of the debris as a fuel source, allowing it to propel itself to another debris object after release (and reduce fuel requirements for subsequent debris rendezvous). The primary focus of the study [18] was on hardware, reduced-model analysis, orbit analysis, and control methodology for capturing debris using the spinning satellite. The proposed method is shown in Fig. 14

In [127], a path optimization strategy for the Space Sweeper with Sling-Sat mission was introduced. The optimization method, which was based on a genetic algorithm, aimed to determine the most efficient sequence of actions for debris removal. The simulation results indicated that 27% of the total mission's $\Delta - V$ corresponded to the required fuel consumption, successfully enabling debris removal. Furthermore, the study demonstrated that the Sling-Sat could remove up to 121 objects over its lifetime, assuming the mission's total available impulse was 4 km/s.

The Sling-Sat method offers a fuel-efficient solution for space debris removal by exploiting existing momentum. It can remove multiple debris objects in a single mission. However, it was found that multiple interactions may be required to remove debris [8]. Further, significant challenges remain in the area of capturing space debris via a spinning spacecraft.

2.13. Alternative methods

In addition to the prominent methods for managing space debris, several innovative unconventional removal techniques are currently being proposed. For example, in [128], a new method for capturing space debris using origami techniques was introduced. This approach eliminated the need for specific grasping points, leveraging its ability to unfold in various ways to adapt and form configurations that securely capture objects of different sizes. The flexible caging configuration can be adjusted based on the size of the debris. Furthermore, the proposed method can be compacted into a smaller form, reducing storage requirements and saving valuable launch space. For small debris ranging from 1 to 10 cm, a soccer-like spherical caging configuration was proposed, comprised of twelve regular pentagonal blades and twenty regular hexagonal blades, all equal in length (see Fig. 15). For larger debris, a three-finger caging configuration was utilized. To enhance the multimodal capture mechanism during the capture process, a sliding control method based on an extended state observer was also proposed.

In [129], an impact capture device for space debris was presented. This device featured an adhesive foot pad, a magnetorheological fluid (MRF) buffer, a force sensor, a distance sensor, and an electronic control system. A spherical joint connected the adhesive foot pad to the device body, allowing the foot to conform to inclined landing surfaces. The force sensor measured the contact force during impact adhesion by positioning it between the spherical joint and the foot pad, while the distance sensor tracked the displacement of the piston rod in the buffer to determine the current buffer distance. The device was connected to the service satellite platform by a tether and was deployed from the satellite to capture debris using adhesives. Once secured, the satellite could pull the debris to a graveyard orbit. This proposed method allowed for a safe standoff distance, suitable for various sizes of debris, and minimizes the risk of generating additional debris.

Fig. 14. Sling-Sat method: a tri-scissor arm approach [126].

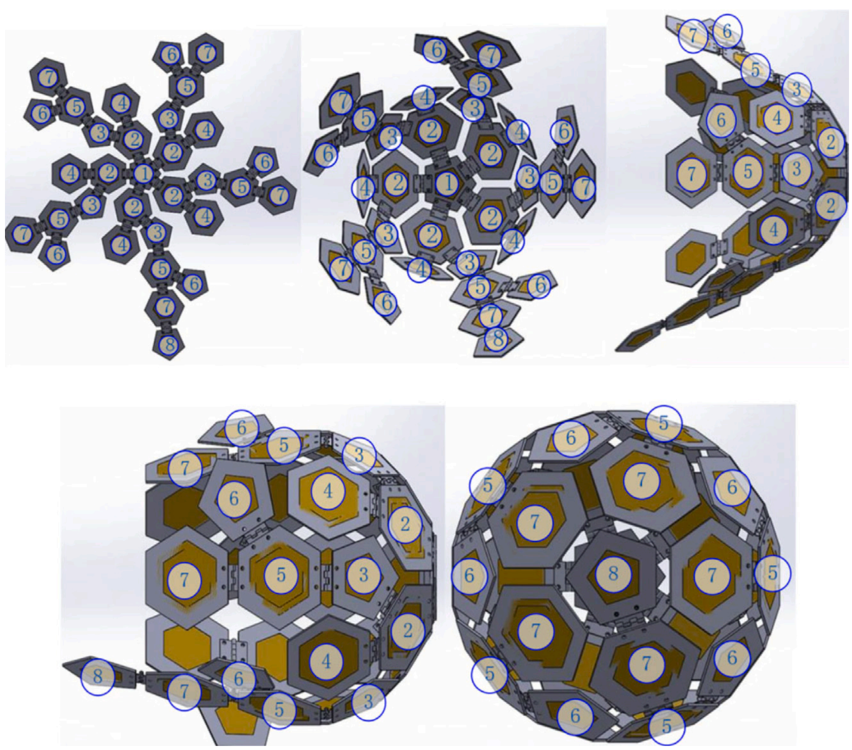

Fig. 15. The formation of a soccer-like structure [128].

2.14. Discussion of space debris removal methods

This study reviewed various space debris removal methods, which can be generally categorized into contact-based methods (such as harpoons, tethered grippers, nets, tentacles, robotic arms, electrodynamic tethers, Deorbiter CubeSats, and Sling-Sats) and contactless methods (including lasers, foam, ion beam shepherds, and solar sails). Each method has its own advantages and disadvantages. This section provides some discussion and comparison for these approaches.

Net-based methods: Net-based space debris removal methods generally offer several advantages: (i) they do not require a precise grasping point on the target, (ii) they are capable of capturing a wide variety of debris types, (iii) they can have less risk of generating fragments, and (iv) they have less dependence on the target's inertial parameters. However, these methods also face challenges, such as difficulties in controlling rapidly rotating targets [22], managing asymmetric net deployment [61], and mitigating the risk of oscillations [23] or net tearing [22] during the capture process.

Tethered gripper-based methods: The tethered gripper has the advantage that its flexible tether can avoid rigid collisions with debris [75, 76], while also enabling efficient capture operation time [23]. However, the method also face challenges when capturing fast-tumbling targets. The difficulty arises mainly from the need to secure a specific grasping point on the target (and may fail entirely if proper alignment is not achieved). Furthermore, due to the flexibility of the tether and the variation in tether length, tethered gripper methods can present complexities during deployment, rendezvous, and the control phases of the capture process [77].

Harpoon-based methods: Harpoon-based methods are effective for mitigating space debris of irregular shapes, as they do not require a specific grasping point and can capture a wide variety of debris types. However, during the approach phase, there is a risk that the harpoon may fail to strike or secure the target, especially due to potential attitude determination errors and delays between target acquisition and harpoon launch. Further unknown material types or degradation of the debris object may impact the effectiveness of harpoon-based methods. Additional experimentation is needed to assess the reliability and practicality of harpoon-based mechanisms. Moreover, because the harpoon physically penetrates the target debris, there is a significant risk of generating fragments, making harpoons less ideal for large-scale space debris mitigation efforts.

Tentacle-based methods: Tentacle-based configurations have generally been considered practical for space debris capture due to their low cost and high reliability, achieved through the use of simple, flight-proven components [15]. However, there has been limited research extending the studies on tentacle-based mechanisms, with much of the focus instead directed towards similar capture technologies, particularly robotic arms. In contrast, tentacle-based methods may be considered inferior to robotic arm-based methods, which tend to have greater controllability during debris capture and post-capture operations.

Robotic arm with hard gripper-based methods: Numerous studies have explored the use of robotic arms equipped with hard grippers for space debris capture. This method can be more readily tested on the ground. However, the rigid nature of these grippers poses a risk of generating fragments during the capture process, potentially contributing to further space debris. In contrast, a space manipulator equipped with a soft gripper could offer a more promising solution. The soft gripper's ability to dissipate impulse upon contact helps reduce the likelihood of fragment generation, making it potentially an effective tool for capturing space debris.

Deorbiting module-based methods: Deorbiting module-based methods have the potential to remove both large and small space debris. However, the rendezvous phase can be complicated, as the mothership must first maneuver to align itself with the target debris, followed by the module performing a rendezvous with the debris. In the case of fast-tumbling targets, there is a risk that the debris may escape during the rendezvous. Additionally, the module may be damaged during the attachment or collision with the debris. Despite these challenges, this approach offers the potential to remove multiple large debris objects through a mothership-based debris remediation strategy that may be more cost-effective than single-spacecraft-single-debris approaches.

Laser-based method: Laser-based methods are contactless space debris removal techniques that have potential to remove various types and size of debris. However, there is a high risk of debris breakup, ejecta plume degradation, and issues handling spinning or tumbling targets [110]. Large debris or debris requiring a significant change in orbit may require long time frames to deorbit, resulting in substantial power consumption. Furthermore, at long distances, the laser's concentration can weaken, reducing its effectiveness.

Ion beam shepherd method: The ion beam shepherd method is a contactless space debris removal technique that uses a collimated beam to deorbit debris. A notable advantage of this method is that it does not require physical contact with the debris object in order to be effective. However, a secondary ion beam thruster is needed to create the opposing force required for it to maintain a hovering position relative to the debris. Further, at greater distances, the ion beam diverges so that it spreads over a larger area, with less force directly exerted on the debris object. Typically deorbiting timelines using the IBS method can have long durations. To mitigate this issue, multiple thrusters may be needed if timely deorbitation of large debris or debris requiring large orbital changes must be performed.

Electrodynamic tethers: The electrodynamic tether holds promise for space debris mitigation, offering the key advantage of not requiring a traditional propulsion system. Additionally, it can enable relatively fast deorbiting of debris [116]. However, challenges arise from the tether's flexibility and variable length, which can complicate its deployment. Increasing the tether length may also induce oscillations, while high-velocity debris pose a risk to the tether's stability and could potentially cause damage upon impact.

Solar sail-based methods: Solar sails offer a promising method for space debris removal, with the advantage of not requiring external fuel or power. It can also be useful as an end-of-life disposal method for spacecraft without fuel for orbital maneuvering, but that retain attitude control (similar to drag sails for spacecraft in low Earth orbit). However, solar sail-based methods are often slow, and controlling the sail can be challenging. The effectiveness of the sail depends on the angle between its plane and the direction of sunlight, which directly influences the magnitude and direction of the force generated. This dependency limits the effectiveness of solar sails for deorbiting debris in orbits where the sail's plane is perpendicular to the Sun's rays [8]. It also may not be practical for noncooperative debris targets without additional external attitude control.

Foam-based method: Foam-based methods are an innovative approach to space debris removal that do not require a docking system. It enables the removal of multiple debris objects in a single mission by using an electric propulsion system to target and eliminate them sequentially by applying foam to increase their effective drag. One of its key advantages is that the foam mass can be adjusted based on the type of debris, and the foam ball can be customized to achieve the desired deorbiting time. However, for debris weighing over 1 ton, the required foam mass may exceed the mass of the debris itself, making this method less effective for larger objects [14].

Sling-Sat method: The Sling-Sat method provides a fuel-efficient solution for space debris removal by utilizing existing momentum to ricochet itself to subsequent debris targets. It can capture multiple debris objects in a single mission. However, it is often not capable of removing debris in a single interaction, as it requires multiple engagements to fully capture and remove the debris [8]. Further, capturing a debris object using a spinning satellite remains a challenge.

Although all of these methods have their advantages and disadvantages, for contact-based methods some of the most prominent challenges are robustness to errors, uncertainties, and perturbations during capture, as well as avoiding generation of additional debris during the capturing and deorbiting processes. As such, this directly motivates the investigation of soft grippers for space debris removal, due to their flexibility, deformability, and compliance during grasping. The following section explores materials used to develop soft grippers for terrestrial applications, which could also be adapted for space and the harsh conditions presented by the space environment.

3. Soft robotic grippers

Conventional rigid grippers excel in achieving fast operation times and precise position control. However, their rigidity poses a risk of damaging target objects during capture or handling [130–132]. Soft grippers offers a promising solution to address these challenges, as they are made from highly deformable and compliant materials. This enables them to absorb impulses during collisions with a target, thereby enhancing the capturing process [133–135]. These factors make soft robotic grippers an interesting area for future study to determine their suitability for space debris mitigation. Any gripper's performance depends greatly on its stiffness, actuation, and adhesion, which must be carefully considered throughout modeling and design [136]. Various materials can be used for achieving stiffness, adhesion, and actuation including granular jamming, low melting point alloys, electrorheological and magnetorheological materials, shape memory materials, electro and gecko-inspired adhesion. In the following subsections, several types of soft robotic grippers are presented, with discussions on their suitability for and application to the space environment discussed at the end of the section.

3.1. Granular jamming-based grippers

Jamming is a versatile mechanism that has been used to create novel robotic systems and can accomplish significant stiffness variation compared to fluidic actuation, shape memory materials, electrorheological and magnetorheological materials, and electroactive polymers [137]. This review focuses on the most prominent type of jamming that has been explored in robotic grippers, namely, granular jamming. Granular jamming (GJ) employs airtight elastic membranes, packed with either natural or artificial grains. Natural grains include coffee, corn, rice, pepper, and salt; whereas, artificial grains include glass, plastic, rubber, and plastic, cylindrical geometries—with coffee grains and glass being the most commonly used grains for soft robotic application [137].

In [138], a universal passive universal gripper was detailed consisting of a collar, a balloon membrane (with a thickness of 0.33 mm), an air filter, coffee grains, a vacuum line port, a high pressure port, and a base. The membrane was filled with coffee grains and clamped by the collar. The gripper adapts to the shape of the target, and grasps by applying vacuum to remove the air from the membrane, which enables a firm hold. It has actuation times ranging from 0.1 to 1.1 seconds, with holding force varying between 1 and 100 N, and a pinching force of 0.1 to 10 N. The proposed gripper is versatile, capable of utilizing both positive and negative pressure, and excels in capturing objects of various shapes and multiple objects at once. To increase the holding force of a gripper, a modified jamming gripper design was introduced in [139], by incorporating a small nub and fluidizing the granular media. The proposed gripper was comprised of a bag filled with coffee grounds, base, and filters.

In [26], an experiment was conducted to determine the use of a universal granular gripper for heavy industrial applications (*e.g.*, overhead crane use in machine shops and warehouses). The results showed that a granular gripper can lift an irregularly shaped object that weighs up to 120 kg. In [140], a universal gripper was modified by replacing individual fingers with a single mass of a granular material. Once it was applied to an object, the gripper flowed around the object taking on its shape. Pick operations were performed where the gripper was able to adapt to the shape of the object and effectively grasp the targets.

In terms of achieving the desired stiffness various techniques were proposed, *e.g.*, in [141], the passive particle jamming method was introduced that worked without the use of a vacuum or any other kind of control mechanism. The proposed method was used to develop a gripper finger by integrating a silicone rubber soft actuator and a pack of particles. The results showed that the proposed method had a high varying stiffness capability. In [142], a method was introduced that used water instead of air to control the stiffness of a granular jamming joint finger. In [143], a three-fingered soft gripper was developed in which pneumatic muscles were used to actuate the fingers, and granular jamming was used to vary the stiffness.

3.2. Low melting point alloy-based grippers

Recent developments in soft materials have resulted in the development of soft robots that are highly deformable and interact with objects in a more flexible and compliant manner than traditional stiff robots. Compared to other materials, low melting point alloys (LMPA) are more suitable for soft robots because they can transition to a liquid state at relatively low temperatures, *i.e.*, 42.0 °C to 70 °C [27].

In recent years, researchers have started integrating LMPAs to enhance the stiffness and actuation of grippers in their development efforts.*e.g.*, in [27], a novel gripper was developed by incorporating an LMPA into a soft actuator to enhance its bending stiffness. The study also demonstrated that the proposed gripper had a self-healing property, meaning that cracks in the actuator structure were rectified by the reheating-refreezing circle. In [144], a novel variable stiffness actuator was introduced that was composed of a dielectric elastomer actuator (DEA) and silicone substrate with an LMPA implanted in it. The LMPA-embedded silicon substrate offered a controllable stiffness between soft and rigid states, while DEA had bending actuation capability. In [145], a three-fingered electroadhesive gripper based on an LMPA was introduced having variable stiffness capabilities (see Fig. 16). The proposed gripper was able to capture both flat and convex objects, but was unable to grab high-temperature objects (above 47.0 °C).

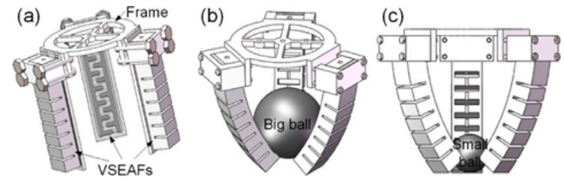

Fig. 16. Three-finger gripper incorporating LMPA and variable stiffness electroadhesive technology. (a) Design of the gripper. (b) An object being wrapped by the gripper's fingers. (c) Capturing an object using the fingertips [145].

3.3. Electrorheological and magnetorheological materials-based grippers

Soft robotics have enormous potential because of exceptional compliance and hyper-redundant capabilities. Electrorheological and magnetorheological fluids are ideal for soft robot applications due to their ability to undergo rapid phase changes from liquid to solid and vice-versa within milliseconds when subjected to electric and magnetic fields, respectively [146]. Various researchers have successfully incorporated these materials into soft robot designs. In [28], fingertip components composed of electrorheological fluids (ERF) are positioned between a grounded elastomer and positively charged electrodes. This setup forms a capacitor, and its capacitance increases when the elastomer is deflected towards the positively charged electrode. When voltage is applied, the electrorheological fluid undergoes a phase change from a Newtonian fluid to a Bingham plastic. This property allows the fingertips to provide high lifting force with minimal grasp forces. In [147], a magnetorheological fluid (MRF) based universal gripper was introduced, which was capable of grasping different shaped objects. The gripper consists of a cup-like bladder jammed with magnetorheological fluid installed on top of an electromagnet. Grippers can also be developed using electrorheological and magnetorheological elastomers, *e.g.*, in [148], a two-finger gripper was developed based on a magnetorheological elastomer (MRE) that was activated by an external electromagnetic source and capable of grasping objects of varying shapes. In [149], two prototype soft grippers based on magnetorheological elastomers were developed. The first prototype consisted of graspers made of silicone and ferromagnetic particles, which were attached to a non-magnetic platform. This prototype was controlled by a solenoidal electromagnet with a neodymium-iron-boron (NdFeB) permanent magnet (PM) core. It was capable of grasping objects of varying shapes and offered fast and easy control. The second prototype comprised three fingers made of silicone encased in magnetorheological elastomer. This prototype was controlled by a single electromagnet with a magnetic core. It was capable of grasping small objects of varying shapes and also exhibits fast dynamics.

3.4. Shape memory materials-based grippers

Grippers composed of shape memory materials have gained popularity because of their excellent capturing capability. Shape memory materials come in the form of either shape memory alloys (SMAs) or polymers (SMPs). These materials, when exposed to an external stimulus, can return to their original shape after being temporarily deformed.

Several researchers have utilized shape memory materials to develop various types of grippers. For example, in [150], a three-fingered

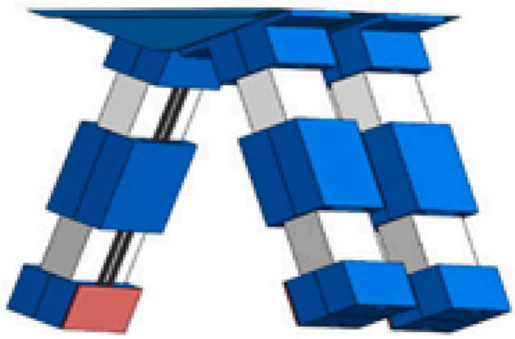

Fig. 17. Proposed three-finger soft gripper featuring SMA technology with variable stiffness offers robust holding at high stiffness and compliant grasping at low stiffness [31].

gripper was developed using shape memory alloys. Shape memory alloys were employed for actuation, while shape memory polymer was used to adjust the stiffness of the finger hinges. The proposed gripper consisted of two SMA wires embedded in a polydimethylsiloxane matrix. Stiffness modulation was incorporated to enhance the gripper's adaptability for capturing objects over a broader range of weights and shapes. One drawback of this gripper was a long transition time from low stiffness to a high stiffness state caused by the slow dissipation of heat in the heated SMP. In [31], a novel soft robotic gripper with three fingers was introduced consisting of nickel–chromium, polylactic acid, SMA wire, silicone rubber, and paraffin. The paraffin, encased in an elastomeric membrane, served as a mechanism to create variable stiffness in the robotic fingers, enabling stiffness adjustment through cooling or heating, while SMA was utilized for actuation. The gripper was able to adapt its robotic fingers to capture irregularly shaped bodies at low stiffness and maintain the deformed shape of the robotic finger while increasing stiffness to lift objects efficiently. The proposed gripper from [31] is shown in Fig. 17.

In [151], a gripper featuring a monolithic compliant mechanism actuated by SMAs was developed. The gripper consists of two jaws, which were controlled by applying heating and cooling to SMAs. Cooling is applied to open the jaws, while joule heating is applied to close and capture the object. The compliant construction of the gripper eliminates the need for movable parts, thereby avoiding friction-related issues. However, SMAs require high current and have limited bandwidth due to their long cooling time. In [152], a soft gripper was developed consisting of pre-bent SMA wire, straight SMA wire, and a spring. An SMA spring was used to actuate the palm of the gripper, with the SMA wire serving as both the actuator and the structural frame of the finger. Additionally, a hook structure was integrated at the fingertip to enable self-locking capabilities. The proposed gripper demonstrates strong grasping performance, achieving a maximum grasping force of up to 1.1 N.

3.5. Electro and gecko-inspired adhesives-based grippers

Gecko-inspired adhesion (GA) uses van der Waals forces, *i.e.*, forces of attraction or repulsion between molecules, which create dipoles that can be either temporary or permanent [153]. Researchers have long been intrigued by the ability of geckos to adhere to surfaces and many have been working to develop artificial adhesives for possible applications in various fields, including robotics, medicine, space technology, and electronics. Further, some researchers are investigating how to incorporate these adhesives into soft grippers. For example, in [154], a two-finger hydraulic driven gripper was developed by integrating two sheet-shaped fabric bending actuators with variable stiffness filament and gecko adhesive. The result shows that the developed gripper was suitable for slippery objects and can capture objects larger than its gripping span. In [34], a gripper was introduced by integrating gecko-inspired adhesives and fluidic elastomer actuators. The gripper offered fast operation speeds and strong gripping forces at lower actuation pressures and for larger grasping curvature. In [155], a soft passive gripper was developed that was comprised of six actuators set out in the form of a star. The bottom part of the actuator was composed of an extensible layer that splits into numerous air chambers to facilitate bending. The bottom of actuator also contained an adhesive layer, while the top part contained an inextensible layer. The passive gripper required energy to release the object, contrary to active grippers that require pressure for holding and gripping the object. The developed gripper was only suitable for flat objects. In [156], a new soft gripper was introduced that integrates both electrostatic and gecko-inspired adhesives. Both types of adhesives are controllable, allowing them to be activated or deactivated as required. The proposed gripper was composed of two fingers and a body structure, with each finger equipped with two tendons for actuation and two rubber tubes. Additionally, there was a rigid piece that connected each finger to the main body. The developed gripper demonstrated a strong capability for gripping objects with high force. In [157], the gecko gripper was proposed, which contained an inflatable membrane and gecko-inspired fibrillar elastomer adhesives. The developed gripper was suitable for picking up and releasing complex and fragile objects.

Other materials that have the potential to enhance gripping capability are electroadhesives. Electroadhesion (EA) is an electrostatic force of attraction between two substances when subjected to an electrical field. Electroadhesion requires four parts: (i) a power source, (ii) a control unit, (iii) an electroadhesive pad, and (iv) a substrate. A voltage is applied to the electrodes to create electroadhesive forces between the electroadhesive pad and substrate. For de-adhesion, the power supply must be turned off. The high-voltage power source is coupled to a control device to regulate the voltage [158]. Various researchers have started using electroadhesives to enhance the gripping capabilities of robotic grippers, *e.g.*, in [33], a grasping system was developed in which a vision system was incorporated into an electroadhesive gripper to capture an object without causing any damage. In [159], a gripper was introduced by integrating electromagnetic adhesion and electroadhesion, which enhanced the gripping capability and allowed it to lift low-density objects. In [160], a pneumatic actuator was integrated with an electroadhesive gripper. The design included two fingers, each constructed using 3D-printed molds. One mold contained negative fluidic channels that formed the primary structure of the pneumatic actuator, while the other accommodated the electroadhesive component. The proposed gripper, known as the PneuEA gripper, had the ability to lift not only thin and flat objects, but also complex-shaped items. In [161], a novel gripper was developed by embedding an electroadhesive composite with dielectric elastomer actuation. The gripper had self-sensing as well as shape-adaptive capabilities. A comparison of various gripper technologies is detailed in Table 1.

3.6. Application of soft robotic grippers in the space environment

Soft robotics holds significant promise for space applications due to their gentle handling capabilities and inherent redundancy. However, deploying soft grippers in space may have considerable challenges due to the harsh space environment. Unlike terrestrial applications, in the space environment soft robots are exposed to substantially different operating conditions, including unique vacuum, radiation, thermal, and upper atmosphere conditions, as well as other hazards, such as space debris and micrometeoroids. This section investigates how space environmental factors can affect the selection of materials in the development of soft grippers. It also provides a brief overview of some of the major complexities associated with implementation of soft robotics in the space environment, discusses the effects, and identifies potential materials capable of mitigating these effects.

Table 1
Comparison of different gripper technologies and their performance parameters.

Ref.	Structure Type	Materials	Control Actuation	Control Stiffness	Control Adhesion	Performance Parameters	Grasping Object
[30]	Two-finger gripper	MRE, twisted and coiled polymer (TCP), laminated composite shell, silicone rubber membrane	MRE	TCP	–	The tensile force is 3.7 N in low stiffness state and 5.5 N in high stiffness state for ball having diameter 20 cm	Suitable for capturing objects of different shapes, including fragile objects, while offering faster response time and high stiffness
[32]	Four-finger gripper	Shape memory polymer resin, carbon fiber, epoxy-based resin	SMP	–	–	Grip force: 2.6 N; Object-to-gripper mass ratio: 106.6	Suitable for objects with various shapes, sizes, stiffness, and weight.
[130]	Soft robotic surface design inspired by the Venus flytrap	SOMOS Imagine 8000, silicone rubber E625	Pneumatic	–	–	With an applied pressure of 60 kPa, the maximum grasp force is 0.71 N and the pull-off force is 8.15 N	Capable of capturing various sized objects
[138]	A vacuum-controlled bag filled with granular material	Coffee grains, silicone elastomer, latex balloon membrane	GJ	GJ	–	The gripping force of the proposed method ranges from 0.1 to 10 N. The holding force spans from 1 to 100 N. The actuation time is between 0.1 and 1.1 s.	Ability to grasp objects of various shapes and sizes Capable of handling multiple objects simultaneously
[145]	Three-finger gripper	LMPA, inflated chamber, electric resistance wires, EA pad	Pneumatic	LMPA	EA	Grabbing force is 10.74 N for an envelope in a rigid state at 60 kPa	Suitable for flat and convex objects
[154]	Two-finger gripper	GA, thermo-responsive variable stiffness filaments (TRFS), fabric bending actuators	Hydraulic	TRFS	GA	The gripper force of the proposed gripper is 9.5 N while pull out is 2.7 N	Capable of capturing slippery objects
[155]	Star-shaped bending actuators gripper	Elastosil M 4601, gray pro resin, gecko nanoplast, plexiglas, elastomeric prepregs, fleece	Pneumatic	–	GA	The gripper has a maximum load capacity of 180 N and a detachment force of 9 N	Capable of capturing flat objects
[156]	Two-finger gripper	Silicone rubber (Mold Star 30), Sylgard 184, electrostatic adhesive pad, Kapton sheet	Servo-driven tendons	–	EA,GA	Gripping forces: 2.15 N (acrylic), 0.36 N (Tyvek fabric), 3.60 N (Kapton)	Suitable for soft, fragile, or irregularly shaped objects, including fabrics with varying roughness
[157]	Ball-shaped Gecko-inspired fibrillar elastomer adhesive gripper	Micro-fiber adhesives, ST-1060 polyurethane, F-25 polyurethane	Pneumatic	–	GA	Maximum picking force: 0.41 N	Suitable for handling a wide range of lightweight objects with various sizes
[162]	Bag filled with granular material, controlled by vacuum	EA pad, coffee grains, silicone elastomer, carbon black-filled elastomer composite	GJ	GJ	EA	The gripping forces for porous and powdered surfaces are 1.1 N and 1.9 N, while for oily, moistened, and dry objects, the forces are 14.8 N, 12.9 N, and 12.6 N, respectively	Suitable for capturing object with a variety of surface properties such as oily, moistened, powdered, and porous
[163]	Three-finger gripper	GA pads, acrylic plate, slider, linear guide, SMA wire, coil springs	SMA	–	GA	The average normal adhesion pressure on the surfaces of carbon fiber, acrylic, glass, and steel was found to be 3.3, 2.75, 2.3, and 2.2 kPa	Suitable for flat surfaces like steel, acrylic, carbon fiber, and glass
[164]	Three legs and three feet gripper	Lithium polymer battery, jeffamine, epoxy monomer, two types of SMP (soft and stiff)	–	SMP	SMP	Single soft SMP, single stiff SMP, and dual SMP have respective average adhesion strengths of 1.75 atm, 2.28 atm, and 4.83 atm	Suitable for flat, smooth, moderately rough, dry and wet surfaces
[165]	Two-finger gripper	Large electrorheological valve, silicone oil	ERF	–	–	Maximum bending angle of the gripper is 140 degrees	Capable of capturing objects of various shapes
[166]	Two-finger gripper	MRF, magnetic elastomer, tactile sensor, pneumatic chamber, electromagnets	Pneumatic	MRF	–	When the MR fluid solidifies, the gripping force increases from 2.11 N to 5.3 N at 160 kPa pressure, increasing the stiffness	Suitable to capture complex shaped objects
[167]	Two-finger gripper	EA pads, spiral spring, EA fixture	Air bubble	–	EA	The flexible gripper's load capacity was 130 ± 2 g under EA force, 203 ± 1 g under mechanical clamping force, and 320 ± 2 g when both EA force and mechanical clamping force were applied simultaneously	Suitable for complex curved surface objects as well as delicate objects
[168]	Three-finger gripper	Stepper motor, three soft pneumatic fingers (each having EA films)	Pneumatic	–	EA	The proposed gripper achieves a maximum gripping force of 7.61 N without the EA and 10.91 N with the EA	Suitable for thin and flat objects
[169]	Three-curved fingers	Polydimethylsiloxane, Sylgard-184, SMA wires (Flexinol, Dynalloy)	SMA	–	–	The proposed gripper can apply maximum force to the object is 1.5 N	Test object used a bottle
[170]	Two-finger gripper	VSEA pad, Dragon Skin 10, Dragon SkinTM	–	Variable stiffness EA	EA	VSEA pads change stiffness within 1 s; Adhesive pressures on various surfaces: 24.2% (flat), 34.8% (convex), 49.3% (concave)	Suitable for curved surfaces and delicate objects
[171]	Two-finger gripper	SMA linear actuator, cross-shear hinge coupler mechanism, gripping claws	SMA	–	–	The gripping force ranges from a minimum of 4 N to a maximum of approximately 7.5 N	Suitable for various shaped objects

Vacuum Environment: In the vacuum environment of space, materials undergo mass loss due to processes such as outgassing, where gases are released due to the low-pressure conditions. It is important to select materials with low outgassing effects. To ensure their suitability and reliability for space applications, materials must undergo testing according to ASTM E-595 [172]. This standard is used to evaluate the total mass loss and the release of volatile condensable materials when materials are exposed to a vacuum environment. Techniques, such as vacuum bakeout and the use of molecular absorbers, can help in minimizing outgassing effects [173]. Silicon CV-1152, CV-1144-0, Aeroglaze Z306, Socomore Aeroglaze Z307, and Aeroglaze A276 are all examples of well-suited materials for use as coatings in space applications due to their low outgassing characteristics and reliability in vacuum environment [174–179]. Databases of material outgassing properties for space applications can be found at [180,181].

Radiation Environment: The space radiation environment is characterized by the presence of various charged particles. There are three main source of charged particles. The first source of charged particles is solar energetic particles, which are high-energy particles resulting from the solar wind, solar flares, and coronal mass ejections. The second source of charged particles is galactic cosmic rays, which consist of high energy protons and heavy ions originating from high energy events outside of our solar system. The third source, the Van Allen radiation belts, forms from the interaction of the first two sources with Earth's magnetic field. When the solar wind reaches Earth's magnetic field, high-energy particles become trapped, creating the Van Allen radiation belts. These charged particles can cause severe damage through their interactions with spacecraft [182]. To mitigate the effects of radiation, radiation shielding and radiation hardening of hardware are typically employed. The most prominent radiation shielding are kevlar, polyethylene, boron nitride nanotubes (BNNTs) [183–186].

Atmospheric Environment: In the upper atmosphere, oxygen atoms are sparse and widely dispersed. When charged particles collide with them, it causes the splitting of oxygen molecules into atomic oxygen. This atomic oxygen can cause significant corrosion and erosion, altering the thermal characteristics of materials. Selecting the appropriate material is essential to mitigate atmospheric environmental effects and prevent corrosion and erosion. Some examples of suitable materials for this include, Kapton/Al_2O_3, SnO_2-coated Kapton, APTES ((3-aminopropyl) triethoxysilane)-modified silica coatings, Titania-coated Kapton, hollow silica nanospheres with transparent polymide films (HSN/PI), SiO_x/NiCr-coated Kapton, SiO_2/Polyhedral Oligomeric Silsesquioxane (POSS)/Kapton, PDMS/SiO_2 [187–196]. Atmospheric environment effects are predominantly present in low Earth orbit (LEO), the effect is negligible in higher orbits.

Orbital Thermal Environment: One of the most critical challenges for spacecraft in the orbital thermal environment is thermal cycling, where temperatures greatly fluctuate when spacecraft transition from eclipsed regions to areas with direct sunlight, or vice versa. These temperature fluctuations between extreme lows and highs can have a significant impact on the mechanical properties of materials and component functionality. Therefore, it is essential to select materials that can withstand both high and low temperatures, and to test components through thermal vacuum testing. As an example, there are some thermal resisting polymers such as polybenzimidazoles and other potential materials that include aero glaze Z306 polyurethane, socomore aero glaze Z307 Polyurethane, Z93P silicate,Z93-C55 silicate,S13GP:6N/LO-1 silicone, AZ-93 silicate,AZ2000 silicate, and AZW/LA-II silicate that have been investigated particularly for their resilience in the orbital thermal environment [174,177,178,197].

Plasma Environment: The plasma environment consists of ionized gases, *i.e.*, carrying positive charges and free electrons, that respond to electric and magnetic fields, and which are influenced by solar activity. Variations in the velocities of spacecraft and these particles can result in ion sputtering or arcing, potentially causing damage to the spacecraft [182,198,199]. There are many techniques including component shielding and grounding that can be employed to mitigate these effects. However, if a soft gripper directly requires the generation of electrical or magnetic fields, this could become an additional challenge for their implementation in the space environment.

Other Environments: In the orbital environment, a spacecraft experience multiple forces such as Earth's gravitational force, inertial centrifugal force due to its motion, solar radiation pressure, and gravity gradient effects. These forces collectively affect the spacecraft's operational dynamics, resulting in a microgravity environment rather than complete weightlessness [200]. As a result, soft grippers that rely on gravity to support capture, grasping, or actuation, may require a design review to ensure they can be effective in microgravity. Additionally, in low-Earth orbit spacecraft can be influenced directly by the Earth's magnetic field. The Earth's magnetic field envelops the Earth, creating the magnetosphere, which traps charged particles. These particles, due to their high speed, pose a risk to spacecraft and can cause damage. Appropriate coating is needed in order to protect from the effect of these particles [182,201]. Lastly, particle impacts (artificial debris or micrometeoroids) is another significant threat to spacecraft. Soft grippers can face both a constant flux of these particles, as well as higher impact events with debris or micrometeoroids. Effective shielding or spacecraft maneuvering is required to mitigate this potential hazard.

Various materials can be utilized in the development of the soft grippers discussed in Section 3, each offering unique characteristics. The space environment requires investigating each of these soft gripper technologies in light of the various environmental impacts to ensure that they will perform as expected. While all of the soft grippers can be considerably affected by some of the space environmental effects, *e.g.*, space debris impact. Atomic oxygen erosion; other effects may disproportionately affect certain soft gripper types. To mitigate deleterious effects, it may be necessary to apply coatings or shielding, to change actuation approaches, to select or develop new materials, or to pursue new soft gripping technologies entirely. The following provides some additional discussion on each of the soft grippers presented with respect to the impact of the space environment:

Granular jamming: To develop a gripper for space applications based on granular jamming, typically, a flexible membrane filled with granular materials (such as corn, rice, or coffee beans), a pump or device for providing gas or air, and a stable base are required. The stiffness of the gripper is adjusted by manipulating the internal pressure using the pump or air supply device. Silicone elastomers, such as S0383-70 and ELA-SA-401, mentioned in [202], hold promise for space applications. These materials may be utilized for developing soft grippers due to their advantageous properties such as low outgassing, resistance to atomic oxygen degradation, and compatibility with ultra-high vacuum conditions. However, these grippers may face several challenges in space, such as the size and bulkiness of the vacuum system required for their operation, exposure to other particle impacts affecting the gripper membrane, microgravity redistributing granular material, and the potential instability caused by grain rearrangement. Extensive research is needed to determine the viability of employing granular jamming grippers in space.

Low melting point alloys: LMPA-based grippers offer varying stiffness capabilities that make them suitable for terrestrial applications. However, low melting point alloys (LMPAs) are generally not suitable for space applications without thermal control due to their characteristic of transitioning to a liquid state at relatively low temperatures, typically between 42.0 °C to 70 °C [27]. Space presents a harsh environment with significant temperature variations, ranging between very low and very high temperatures, depending on a spacecraft's orbit and thermal properties. These conditions may require specialized thermal control for LMPA-grippers in order to ensure that they perform as expected.

Electrorheological or magnetorheological materials: Developing a gripper by employing electrorheological or magnetorheological fluids and elastomers can be a viable solution for space application because they are easy to control by just applying electric and magnetic fields and the operation time is very short. However, employing these materials to develop grippers for space applications, requires appropriate coatings that can withstand space environment. Further, the plasma environment may create a challenge for their operation and could result in spacecraft charging or differential charging leading to electrical arcing. This remains an open area of research to determine the suitability of these gripper for space environments.

Shape memory materials: Shape memory materials, such as shape memory alloys and shape memory polymers, are capable of returning to their original shape after being deformed when exposed to an external stimulus. In the context of space applications, shape memory polymers can undergo outgassing, which can be a concern due to the vacuum environment. To address this, certain types of shape memory materials are being developed that exhibit low outgassing characteristics. For instance, epoxy-based shape memory composites are engineered to minimize outgassing and may be suitable for developing a gripper for space applications [203]. Shape memory polyimide and shape memory cyanate ester, as well as titanium nick elide–based (TiNi) shape memory alloy [204–207], can also be promising materials for space applications. However, potential challenge lies in their slower transition times, which could impact the efficiency of the capturing process. Further, in terrestrial applications heat dissipation when transitioning states is facilitated by convection, which is negligible in the vacuum of the orbital thermal environment. As a result, heat generated must be released via radiation or through conduction to the spacecraft (which could be undesirable), and may necessitate active thermal control of shape memory material-based grippers.

Electroadhesives and Gecko-inspired adhesives: Gecko-inspired adhesives leverage Van der Waals forces for strong adhesion, making them effective for capturing objects on both slippery and rough surfaces under normal conditions. Polymers are widely utilized as the predominant materials in dry gecko adhesives. Some suitable materials for space applications include silicone rubbers, polyurethanes, polyimides, thermoplastic elastomers, fluoroelastomers, and carbon nano tubes as detailed in [208]. However, polymers may be vulnerable to the space environment due to factors such as outgassing, the effects of atomic oxygen, thermal cycling, ultraviolet degradation, and other hazards. Some polymers have low outgassing characteristics and may be suitable for space applications [208]. There was a study [209] that developed gecko adhesives pads using silicone polydimethylsiloxane (PDMS) and Dow Corning Sylgard 170. These adhesive pads were resistant to thermal and radiation hazards; however, they are expected to be less effective in low Earth orbit due to atomic oxygen exposure, which causes erosion of surfaces. It is also possible that some soft gripping approaches, may be more viable for geostationary Earth orbit applications, where the presence of atomic oxygen is negligible. Similarly, grippers based on electroadhesives offer rapid adhesion capabilities and can be viable for space applications if the materials used to develop the grippers are space-compliant, such as copper-clad polyimide encapsulated by polymers [158,210]. One study, as detailed in [211], investigated the use of electrostatic pads for space applications. These pads were hybrid electrostatic gecko pads designed with copper electrodes arranged in a comb pattern and adhered to a Kapton surface. The exposed trace of the electrode was enclosed in the silicone rubber of a gecko-inspired adhesive, which functioned as the dielectric material. The hybrid electrostatic gecko pads were used to develop a micro climbing robot. Practical demonstrations were performed in zero gravity. Hence, electroadhesives can be viable for developing a soft gripper for space debris removal applications, provided careful selection of materials to ensure the gripper can withstand the harsh space environment.

4. Identification of inertial parameters

Various methods for space debris removal have been discussed, each with different requirements for inertial parameter estimation. Some methods, such as robotic arms or tethered grippers, necessitate accurate estimation of inertial parameters for effective target capture and removal. In contrast, other approaches, like net capturing or laser-based methods, do not rely as strongly on such estimations (though this knowledge can improve their effectiveness). Soft grippers for space debris removal, while more robust to errors in the inertial parameter estimation, would still require some inertial parameter estimation to ensure successful target acquisition and removal. This section reviews techniques for estimating inertial parameters, particularly when a target may be non-cooperative and/or tumbling.

The capture of a non-cooperative target is often made more challenging due to a lack of prior information of inertial parameters and uncertain motion of the tumbling target. As a result, inertial parameter estimation of a non-cooperative target is usually necessary to effectively capture and detumble a target while avoiding collision between the space manipulator and the target and detumble it smoothly. Inertial parameters consist of six components of the inertia tensor, as well as the mass and the position of the center of mass. These inertial parameters are commonly estimated using vision-based and momentum-based techniques. In vision-based methods, cameras are generally used to estimate the inertial parameters without making any physical contact with the target and are primarily used during the pre-capturing phase. In momentum-based methods physical contact is required with the target to estimate the inertial parameters and are typically utilized during the post-capturing phase. In the following sections vision- and momentum-based techniques for estimating the inertial parameters of a target are summarized.

4.1. Vision-based estimation

Various methods have been proposed to estimate the inertial parameters of targets by using data acquired from vision sensors, *e.g.*, in [212], an estimation method was introduced that used 3-D vision sensors to estimate inertial parameters. The method was composed of kinematic data fusion, Kalman filtering, and shape estimation parts and was found to be suitable for harsh sensing conditions, due it not depending on feature detection schemes, optical flow, or model matching. In [213], a method was introduced that used laser range data or stereo vision to estimate the inertial parameters of a tumbling target. The method was useful for long term prediction, facilitating planning of complex maneuvers as well tracking during long phases without observation.

Since the space environment has harsh lighting conditions, which may cause conventional vision-based approaches to fail, a measurement system was introduced in [214], that integrates 3D laser data with stereo vision information and then determines the inertial parameters by employing an extended Kalman filter. The proposed method was robust against harsh lighting conditions. In [215], an architecture was proposed to simultaneously estimate the state, shape, and model parameters of a target. The proposed approach consists of three main steps: data fusion, Kalman filtering, and shape estimation. The method was robust to harsh sensing conditions in space due to its independence from feature detection or model matching methods. Furthermore, the method achieved computational efficiency by leveraging only coarse measurements for the Kalman filter.

In [216], a method was proposed that used optical sensor data to estimate the center of mass and moment of inertia of a target. The method was based on kinematic equations of motion and conservation of angular momentum, which were later solved using a least square methods. In [217], a scheme combining prediction and motion methods for long-term prediction was introduced. The scheme was based on a Kalman filter to determine the states and dynamics parameters of a tumbling target from noisy measurements of a camera system. Subsequently, a guidance scheme utilized the estimated states and parameters for trajectory planning, enabling the robotic manipulator to intercept a grapple fixture on the object. In [218], a filtering method was introduced based on maximum a posteriori (MAP) and iterated extended Kalman filters that used stereovision to determine the relative states (pose and motion) between two noncooperative satellites. In [219], an adaptive Kalman filter was introduced to predict the relative motion and pose of two satellites. The result showed that the proposed method worked well even when the vision system was fully occluded for a short period of time. In [36], an algorithm employing an extended Kalman filter was introduced to estimate the inertial parameters. The method utilized observational measurements in the form of three non-colinear feature points on the target, instead of utilizing relative position and pose information. The results indicated that the proposed estimation algorithm performed well, converging within an appropriate time frame. In [220], a real-time vision-based scheme was introduced that used photogrammetry and an extended Kalman filter to determine the pose and motion estimation. The proposed scheme was used for manipulators to achieve autonomous capture using position-based visual servoing and was effective in preventing tracking failures caused by image noise and actuation delays.

Vision-based techniques can be efficient, since they do not require any physical contact with the target to estimate the inertial parameters, but it cannot easily estimate all inertial parameters, namely, the mass and center of mass, which are necessary for stabilization of the system.

4.2. Momentum-based estimation

Force and momentum-based approaches are often used to estimate the inertial parameters for capture and post-capture operations. Momentum-based methods are based on the principle of conservation of momentum or impulse–momentum theory. In the past various methods have been introduced to estimate the inertial parameters by using momentum-based techniques, *e.g.*, in [221], a parameters identification method was introduced that was based on kinematic equations and conservation of angular momentum to estimate all the inertial parameters necessary to fully reconstruct the free-flying joint space dynamics of the system. The method did not rely on acceleration measurements and was less prone to sensor noise. In [39], momentum identification methods were formulated based on the linear and angular momentum equations of the space manipulator, while forced-based methods were derived by their derivatives, which were both solved by employing the modified recursive least square method. Both the momentum-based and forced-based methods were capable of identifying all inertial parameters of the base and the unknown target at the same time.

In [222], inertial parameters were estimated by exerting an impulse on the target by a rod and information was gathered by using vision and force sensors for the pre-capturing phase. Impulse and kinematic equations were used to model the method. In [223], a momentum-based online, one-step identification method was introduced to capture unknown targets using an on-orbit robotic manipulator with unknown initial linear and angular momentum in the post-capture phase. A traditional recursive least squares (RLS) method was modified in order to estimate the inertia tensor of the target. In [224], a method was introduced based on conservation of angular momentum of a free-floating space manipulator, while considering non-zero angular momentum. Only a few parameters, *i.e.*, spacecraft attitude and angular velocity, joint angles, and joint rates, were needed for estimation of the combined spacecraft, manipulator, and payload inertial parameters. In [225], vision and force-moment data were used to estimate all components of the inertial parameters. Force-moment data was gathered by gently touching the target with a flexible rod. In [226], a new methodology was introduced in which a space manipulator gently touched the target to change the motion of the target in order to obtain the resulting change in the momentum. Then, momentum-conservation was utilized to estimate all components of the inertial parameters.

Momentum-based techniques are useful for estimating inertial parameters that are necessary to capture and detumble a target as well as stabilize the combined system post-capture. However, the manipulator has to make contact with the debris to estimate parameters, which may result in damage to the capturing or target spacecraft. Momentum-based techniques may be synergistic with soft gripper mechanisms, since soft grippers can often dissipate energy during contact, which can facilitate detumbling the target and stabilizing the system.

5. Teleoperation systems

The concept of teleoperation was initially introduced in the early 1900s [227]. However, the first leader–follower teleoperation system emerged in the 1940s [228]. An early and notable application of teleoperation systems was in deep-sea exploration. Even today, teleoperated submarines continue to play a important role in numerous deep-sea operations. Teleoperation systems have since been applied widely, including in military operations, surgical procedures, space exploration, mining, and other fields [229,230].

Teleoperation systems play a vital role in space missions by enabling robots to explore environments that are difficult, costly, or hazardous for humans to access directly. With the use of improved teleoperation systems, operators can interact effectively with a telerobot or spacecraft to complete complex tasks with precision. One notable example is the Rotex mission in 1993, which achieved a significant milestone as the first multisensory robot remotely controlled in space. Rotex operated in two modes, namely, pre-programmed sequences and teleoperation [231].

Teleoperation systems are broadly classified into two main types: direct and supervisory teleoperation. In direct teleoperation, teleoperators use traditional controllers to operate the system or robot based on visual feedback. Direct control mode is also known as forced control mode [232]. In supervisory teleoperation, both the robot and the operator share responsibility and exercise hybrid control over the entire system [232–235].

Space manipulators are typically operated by ground operators. A major challenge in space robotic teleoperation systems is the occurrence of time delays, which can result from factors such as data processing delays, radio transmission delays, and round-trip time delays [44]. These delayed feedback signals, including vision, force, and other forms of feedback, can mislead operators and jeopardize operations. Various techniques have been proposed in the past to mitigate time delay issues and to enhance the communication between leader and follower. For example, in [236], a sophisticated virtual fixture was introduced that provides virtual force feedback to operators, facilitating remote operation processes. The system included a tube-type virtual fixture and a velocity-based virtual fixture. The tube-type virtual fixture guided the robot's end-effector towards the target safely and swiftly over long distances. Meanwhile, the velocity-based fixture utilized force feedback to guide the manipulator towards nearby targets and prevent collisions with the target. Two experiments were conducted using the virtual 6-DOF space robot platform, namely, remote obstacle avoidance and close observation. Results indicated that this approach could reduce operation time and enhance operational efficiency.

In [237], a teleoperation system was developed for a dual-arm space manipulator, comprising of a ground system, a space system, and a software development module. The space system was comprised of a dual-arm manipulator, referred to as the follower arms. Each arm had 7 degree of freedom, was equipped with a three finger grasper capable of grasping various objects. The ground station was equipped with a single leader arm utilizing a 6 degree of freedom haptic interface device. The study introduced novel concepts, such as the virtual grip, which accurately represented the position and orientation of the haptic interface grip in the graphical environment, and the virtual ball, which visually displayed the workspace of the haptic interface. The proposed method helped to identify workspace limitations of the haptic interface encountered in the unsynchronized leader–follower mode, while also facilitating the determination of relative differences between the haptic interface and the posture of the follower arm.

In [238], a teleoperation system was introduced that utilized a combination of force and motion commands for operating the ETS-VII manipulator in orbit. The proposed system included both space and ground components. The space system consisted of the ETS-VII and Tracking and Data Relay Satellite (TDRS), while the ground system included the NASDA satellite-operation system and an operator support system. The operator control system incorporated a 6 degree of freedom compact haptic interface and a mixed force and motion command system. To evaluate the effectiveness of the proposed system, surface tracking and peg-in-hole tasks were performed with and without deliberately introducing modeling errors. Time delays were also incorporated to evaluate the system's performance. The results demonstrated that the system effectively handled modeling errors, mitigated some time delays, and was suitable for many real-time space robotic applications. However, the proposed system lack an immersive environment necessary to enhance situational awareness and facilitate smooth operations.

Virtual reality (VR) and mixed reality (MR) technologies have emerged as effective solutions to mitigate time delays [45]. These technologies enhance situational awareness and provide intuitive control interfaces, enabling more precise and responsive operations [239]. The following section discusses virtual and mixed reality-based teleoperation systems.

5.1. Virtual and mixed reality teleoperation

The application of using mixed reality and virtual reality in terrestrial robotics is increasing due to rapid hardware advancements. Generally, it is understood that VR- and MR-based teleoperation have the capability of mitigating the impact of time delays and enhancing situational awareness during operations [44]. Several research efforts have leveraged MR and VR technologies, *e.g.*, in [240], a teleoperation system that integrates virtual and real-world environments was introduced, enhancing situational awareness through visual feedback. This system included two distinct control modes: coarse movement mode and fine movement mode, aimed at improving long-distance and precise movements. Their combination contributed to smoother manipulator motion. The study also proposed a fuzzy logic-based method to control the manipulator's orientation, position, velocity, and force control, ultimately, enhancing the overall maneuverability of the system. Furthermore, control laws were formulated by using a barrier Lyapunov function method and a backstepping method to maintain the stability of the system within state constraints.

In [241], a teleoperation system was developed based on virtual reality to mitigate the geometrical errors (position error) between real and virtual worlds. The system consisted of three main components: the leader arm, the follower arm, and the virtual arm, all were controlled using velocity commands. Each arm leverages force control and velocity control modes that toggle independently. Force data was used by the arms to detect contact and autonomously change their control mode. While the proposed system effectively mitigated geometric errors, it did not address dynamic errors (*i.e.*, due to force or motion).

In [242], a VR-based telerobotic system was developed that used visual and haptic feedback for compliance tasks. The system was also equipped with a local intelligence controller. The developed system was able to mitigate the time delay issue and offer realistic telepresence.

In [44], a teleoperation system was developed using virtual reality for a space robot manipulator. This system addressed modeling discrepancies between the real and virtual environments by integrating model matching and robot compliance control algorithms. Visual and joint position sensors were employed to achieve model matching and calibrate the virtual model. The compliance control algorithms, such as PD position control, Cartesian impedance control, and hybrid position/force control, were employed to effectively reduce modeling errors.

In [243], a teleoperation system that combines haptic bilateral teleoperation with a virtual workspace was introduced, allowing operators to perform precise trajectory following tasks in dynamic environments. The system was composed of three main components: the leader workspace, the follower workspace, and the virtual workspace. In the leader workspace, a Phantom Omni device was used to receive force feedback and transmit instructions to the virtual workspace. There was also a screen in the leader workspace that showcased visual feedback gathered from the virtual workspace. The follower workspace included a KUKA robot and Kinect RGB-D camera. The workspace operated effectively without requiring force sensors or proximity sensors. The virtual point cloud data was utilized to create a virtual workspace. The study compared two inverse kinematic teleoperation modes: proportional workspace and delta end-effector movements, concluding that proportional workspace was more suitable for a haptic teleoperation methodology. The proposed system successfully minimized the average error between the robot's end-effector trajectory and the desired trajectory, thereby reducing the risk of collisions with objects.

In [244], an optimized BundleFusion algorithm was developed for real-time 3D reconstruction of an agricultural environment in a VR-based teleoperation system. A Microsoft Kinect depth camera was utilized for the 3D reconstruction process. After completing the reconstruction, the model was transmitted to the server-side using wired or wireless networks for real-time management. Subsequently, operators were able to visualize the model in real-time using a VR headset for teleoperation, following its retrieval from the server. This study effectively addressed large-scale, dense, real-time 3D reconstruction challenges in unstructured agricultural environments. The proposed algorithm offered fast frame processing times and produced high-quality, realistic 3D models.

In [245], a novel teleoperation system was introduced that integrated simultaneous localization and mapping (SLAM), providing operators with an immersive telepresence to effectively manipulate a robot in unfamiliar environments. The system employed an RGB-depth camera mounted on the manipulator to capture and reconstruct the environment. A head-mounted display presented a 3D reconstruction of the surroundings, featuring a virtual model of the physical robot. Visual aids within the 3D reconstructed environment provided direction and distance information from the manipulator to the target. Operators could manipulate the real robot using its virtual counterpart in the VR environment. Comparative results with video-based teleoperation demonstrated that the proposed system achieved a higher grasping success rate and in less operation time.

In [246], a teleoperation system called MRVF, was presented that combined mixed reality and virtual fixtures to create an immersive environment for tele-welding. The system included components such as a welding robot, visualization system, haptic leader robot, and the communication framework between the robot and operator space. The MRVF incorporated virtual fixtures to aid in collision avoidance, enhancing operator experience through real-time visual and haptic feedback from the robot. The proposed system also aimed to empower inexperienced or unskilled welders to perform tasks more effectively by leveraging these technological enhancements.

Virtual reality and mixed reality have proven to be effective solutions for mitigating issues caused by time delays and enhancing situational awareness in terrestrial applications. These technologies hold promise as solutions for addressing similar challenges in space applications. The next section discusses the specific challenges that VR and MR teleoperation may encounter in the space environment.

5.2. Applications of virtual and mixed reality teleoperation systems in the space environment

The harsh space environment can have various effects on spacecraft and manipulators, potentially compromising the stability of teleoperation. Other challenges arising from the space environment include challenges, such as time delays, 3D reconstruction problems, limited bandwidth, and modeling errors.

Time delay: In terrestrial applications, virtual reality and mixed reality show promise in mitigating challenges caused by time delay issues. However, further research is needed for their viability in space applications, particularly for tasks like space debris removal or on-orbit servicing, where ground-based teleoperation is typically employed and time delay can significantly impact operations. In particular, the duration of the time delay can be significant depending on the location of the system being controlled, *e.g.*, Earth orbit, lunar surface, martian surface, deep space.

3D Reconstruction issue: In the dynamic and harsh environment of space, a high-quality camera is needed for accurate 3D reconstruction, enabling operators to visualize and enhance their understanding of the environment. In particular, the lighting conditions can be very dynamic—rapidly moving from shadowed or eclipsed locations to areas with direct, high-intensity sunlight, and even situations where the spacecraft themselves glow [247]. Disturbances or distortions in the camera can adversely affect operators, potentially leading to mission failure. Further, visualization algorithms must be robust to dynamic, unstructured environments with poor lighting conditions. Therefore, robust and reliable cameras and algorithms are important for the effectiveness of mixed reality and virtual reality systems for space applications.

Bandwidth: Mixed reality-based teleoperation and virtual reality may require high bandwidth to send data between space and ground stations. Low bandwidth can make it difficult to control the robot and may cause mission failure [248]. Therefore, it is necessary to either use a high-bandwidth system for reliable data transmission or develop an efficient MR or VR system that operates effectively with low bandwidth. Future research needs to focus on making MR and VR-based teleoperation approaches more bandwidth efficient to enable their application on spacecraft.

Modeling errors: There are two types of modeling errors: geometrical and dynamic errors. Geometrical errors involve inaccuracies in position, while dynamic errors, refer to force and motion errors. In teleoperation, where, for example, a leader arm controls a follower arm, discrepancies between virtual and real-world conditions can lead to significant contact forces that may disrupt the contact task. Therefore, it is important to mitigate these errors to ensure smooth performance in teleoperation using mixed reality and virtual reality.

Mixed reality and virtual reality-based teleoperation systems can be a promising solution for space debris removal because they have the potential to not only reduce challenges associated with time delays, but also to enhance the user experience. They may help the user to find a more intuitive and viable grasping point on the debris object, and, hence, facilitate capture. Further research is needed to overcome some of the challenges mentioned regarding time delays, 3D reconstruction, bandwidth requirements, and modeling errors, prior to their application to space missions.

6. Future development

It is expected that future work will focus on addressing the knowledge gaps identified across the various methods and exploring the integration of soft gripper technologies with on-orbit robotic systems. Based on an review of conventional space debris removal methods and an evaluation of key technologies and challenges, the following six areas are suggested for further study.

Advancements in control strategies for prominent debris removal methods: This study reviewed prominent active debris removal methods, highlighting key challenges such as the complex rendezvous phase, difficulty in capturing fast-tumbling targets, the impact of unknown disturbances and uncertainties, extended capture or deorbiting times, potential self-collisions in robotic arm systems, and oscillations experienced by tethers during capture—all of which need to be addressed. Nonlinear control methods or artificial intelligence (AI)-based control strategies could help mitigate these issues. Additionally, the materials and structural integrity of removal systems may also affect their performance in capturing or deorbiting targets, representing another open area for research. Future research should address these challenges, as finding solutions will be essential for the effective mitigation of space debris.

Advancements in visual technologies for capturing space debris: To mitigate space debris, advances in detection and characterization algorithms for cameras or lidar systems are essential for determining the size, shape, and behavior of a target. These technologies can play a critical role in capturing or deorbiting debris and in estimating their behavior. Using visual cameras, images of the debris can be captured to identify the grasping point or area of interest. Computer vision and artificial intelligence techniques can be utilized to identify the regions of interest, enhancing the efficiency of the capturing and deorbiting process. Future research in these areas is needed, as advancements in visual technologies, computer vision, and AI techniques will improve the accuracy of region-of-interest or grasping position estimation and enhance the ability to determine the shape of debris for more effective removal.

Advancements in inertial parameter estimation techniques: To capture or deorbit space debris using a robotic arm, estimating inertial parameters is essential. This paper reviewed two prominent methods for estimating inertial parameters: visual-based and momentum-based approaches. However, both methods have limitations. Visual-based methods cannot estimate all inertial parameters, while momentum-based methods require physical contact with the debris, which could potentially damage either the debris or the robotic end-effector or both. To address these issues, a soft gripper could be employed, as it has the ability to absorb impulses and measure all inertial parameters. Combining both momentum and visual-based methods with a soft gripper technology could allow for more efficient and accurate estimation of all inertial parameters. This presents an open area for research, as the material composition of the soft gripper may also influence the accuracy of inertial parameter estimation.

Advancements in soft gripper technology: For the effective use of a soft gripper in space debris removal, careful design is needed to ensure the system is appropriate for the space environment. This study explores various materials that have been employed in terrestrial applications for actuation, adhesion, and stiffness. It also examines potential coating materials that would enable the gripper to withstand the harsh conditions of the space environment. Additionally, other actuation materials, such as hydrogels, dielectric elastomer actuators, conductive polymers, ionic polymer–metal composites, magneto-responsive elastomers, and liquid crystal polymers, should also be explored. For actuation methods, options such as pneumatic, hydraulic, mechanical, and electrically-driven actuation can also be explored—always with the intention of developing a soft gripper suitable for the space environment. When evaluating performance, parameters such as gripping force, load capacity, response speed, strain, strain rate, pressure, and stiffness may need to be considered. Additionally, artificial intelligence and nonlinear control methods can be applied to enhance the efficiency of debris capture. The performance of the gripper can be validated through various tests such as finger strength, grasp strength, thermal testing, and resistance tests. These areas require further research, offering opportunities for future exploration and development.

Artificial intelligence in virtual and mixed reality-based teleoperation systems: Capturing space debris through mixed reality-based teleoperation can be highly effective, as it enhances situational awareness and provides the user with detailed information about the target. By integrating artificial intelligence into the mixed reality system, the system can automatically recognize debris based on pre-trained models and perform tasks autonomously, leading to faster and more accurate operations. This integration also creates a more realistic environment, improving the interpretation of complex situations and interactions, which can help reduce time delays during the capture process. This presents an open area for research and exploration, offering opportunities for further advancement of terrestrial technologies for application in the space domain.

7. Conclusion

The space debris removal methods reviewed in this study include: net-based methods, tethered gripper-based methods, harpoon-based methods, tentacle-based systems, robotic arms with hard grippers, deorbiting module-based methods, lasers, ion beam shepherd, Sling-Sat, electrodynamic tethers, solar sails, and foam-based methods. Each method exhibits advantages and disadvantages. In case of the rigid methods, robotic arms have the capability to capture various kinds of debris but exhibit stiff composite behavior, which may increase the risk of generating fragments. Deorbiter modules are also suitable for various kinds of debris but have a complicated rendezvous phase and do not handle fast-tumbling targets well. Tentacles are effective in capturing specific targets known a priori, but exhibit stiff composite behavior. With respect to flexible methods, the net-based methods are suitable for capturing any kind of debris and do not require a grasping point on the target. However, there is a risk of the net tearing during the capturing phase and difficulty in dealing with fast-tumbling targets. Tethered harpoons can capture various types of debris but are prone to the risk of generating fragments on impact. Tethered grippers are also suitable for capturing various kinds of debris but can face challenges with deployment complexity and control during the capturing phase. The details of each method, along with their advantages and disadvantages, have been extensively discussed in Section 2.

This paper also examined soft robotic grippers and their potential application to space debris removal, particularly due to their suitability for compliant capture behavior that may reduce the risk of target fracture or fragmentation. The soft gripping technologies discussed include granular jamming0based grippers, low melting point alloy-based grippers, electro- and magnetorheological fluids and elastomer-based grippers, shape memory materials-based grippers, electroadhesives, and gecko-inspired adhesives. These approaches offer unique advantages in terrestrial applications, but not all are easily adapted for the space environment. For example, electro-magnetorheological fluids and elastomers are easy to control by simply applying electric and magnetic fields, resulting in a swift response time. However, they may experience challenges with respect to charging in the plasma environment as well as outgassing in the vacuum environment of space. Shape memory materials offer varying stiffness capabilities through temperature control, but the orbital thermal environment may require more sophisticated thermal control systems to ensure the actuators operate as desired. Gecko-inspired adhesives have the capability to capture slippery and rough surfaces objects and electroadhesion offers fast adhesion; however, their surfaces may be adversely affected by outgassing, atomix oxygen attack, and other degradation from the space environment. Further, the application of protective coatings, a common approach in spacecraft design, may not be viable if adhesion-based approaches are used. Ultimately, these soft gripping technologies may be viable for capturing space debris and space applications. However, their development and deployment require careful consideration due to the harsh space environment.

To efficiently and effectively capture space debris using contact-based active debris removal methods, such as robotic arms with hard grippers or tethered grippers, accurate estimation of inertial parameters is essential to predict the required forces and torques necessary to secure a strong grasp hold and maintain connection with the debris after grasping. Therefore, methods for estimating these parameters were also discussed. Inertial parameters estimation is essential in order to capture, detumble, and deorbit a target as well as to control a space robot or combined system post-capture when contact-based methods are used. This paper reviewed both vision-based and momentum-based methods, each with their advantages and disadvantages, *e.g.*, vision-based method offer non-contact estimation, but may not be able to estimate all inertial parameters accurately and could be affected by space lighting conditions, potentially leading to inaccurate estimations. In contrast, momentum-based methods can estimate all inertial parameters more accurately. However, they require physical contact with the debris, which is usually achieved using a robotic arm equipped with a hard gripper or a rigid attachment. This approach poses the risk of debris breakup due to the stiffness of the gripper. To mitigate the risk of debris breakup and accurately estimate all the inertial parameters, employing a soft gripper could be a viable solution. A soft gripper provides a gentle approach for physical contact with the debris, often dissipating energy during contact, which can potentially reduce the risk of generating fragmentation. However, challenges related to time delays still remain a challenge during the capture phase using direct control or teleoperation.

Hence, this study also explored the state-of-the-art in teleoperation systems and the applicability of virtual reality and mixed reality-based teleoperation systems to the space environment. Traditional teleoperation systems suffer from time delay issues and often limited situational awareness. Virtual reality and mixed reality technologies have emerged as leading solutions to address these issues by mitigating the impact of time delay challenges and enhancing situational awareness. However, challenges remain, such as high bandwidth and low modeling error requirements, which must be addressed before these systems can be effectively employed in an unstructured and dynamic space environment.

CRediT authorship contribution statement

Muneeb Arshad: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Michael C.F. Bazzocchi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Faraz Hussain:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

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

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