Robust Capture and Deorbit of Rocket Body Debris Using Controllable Dry Adhesion

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Abstract—**Removing large orbital debris in a safe, robust, and cost-effective manner is a long-standing challenge, having serious implications for LEO satellite safety and access to space. Many studies have focused on the deorbit of spent rocket bodies (R/Bs) as an achievable and high-priority first step. However, major difficulties arise from the R/Bs' residual tumble and lack of traditional docking/grasping fixtures. Previously investigated docking strategies often require complex and risky approach maneuvers or have a high chance of producing additional debris. To address this challenge, this paper investigates the use of controllable dry adhesives (CDAs), also known as gecko-inspired adhesives, as an alternative approach to R/B docking and deorbiting. CDAs are gathering interest for in-space grasping and manipulation due to their ability to controllably attach to and detach from any smooth, clean surface, including flat and curved surfaces. Such capability significantly expands the number and types of potential docking locations on a target. CDAs are also inexpensive, are space-qualified (performing well in a vacuum, in extreme temperatures, and under radiation), and can attach and detach while applying minimal force to a target surface, all important considerations for space deployment. In this paper, we investigate a notional strategy for initial capture and stabilization of a R/B having multi-axis tumble, exploiting the unique properties of CDA grippers to reduce maneuver complexity, and we propose alternatives for rigidly attaching deorbiting kits to a R/B. Simulations based on experimentally verified models of CDA grippers show that these approaches show promise as robust alternatives to previously explored methods.**

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1. Introduction

The accumulation of debris in low-Earth orbit (LEO) is a well-documented and growing hazard to future space operations. The U.S. Space Surveillance Network is currently tracking over 13,000 large debris objects of size class $>$10 cm. However, there are estimates of over 500,000 debris objects in LEO sized $>$1 cm [1]. Given the average LEO collision velocity of around 10 km/s [2], these objects are difficult or impossible to shield against. Indeed, the heavily shielded US modules of the International Space Station (ISS) are only rated to withstand $\sim$1.4 cm diameter debris impacts. Thus, each of these objects, most of which are too small to track, is large enough to disable the broad majority of colliding spacecraft. In the past 5 years alone, NASA has executed or assisted in over 100 collision avoidance maneuvers of the ISS and robotic spacecraft to prevent such impacts.

Large-scale hypervelocity collisions are rare but devastating events. The most significant accidental collision to date occurred in 2009 between the functioning Iridium 33 and the deactivated Cosmos 2251 satellite, generating over 2,200 pieces of large catalogued debris and many more smaller fragments. In 7 years since, only 35% of the large debris from this event have decayed and the remainder accounts for 11% of the total catalogued debris on orbit [3].

Since the seminal work by Kessler in 1978 [4], there has been awareness of a critical threshold after which the orbital debris cloud becomes self-sustaining and continues to grow. Recent parametric studies have suggested that this threshold has been surpassed [5, 6]. Though debris clouds in MEO and GEO are projected to show only moderate growth, a major accidental collision is expected in LEO every $\sim$5 years, leading to rapid nonlinear increase in the number of large debris fragments. Even if no new launches occur or if stringent debris mitigation standards are imposed on new spacecraft (e.g. ensuring orbital decay within 25 years or preventing other debris-generating events such as battery or unused fuel explosions), the LEO debris field will continue to grow.

These findings have demonstrated the need for active debris removal (ADR), targeting objects of high debris-generating potential. Deorbiting targets can be prioritized by their total mass (i.e. potential to produce a high number of large fragments) and probability of a major collision, judged by factors such as the crowding of their orbits and their estimated decay time [7, 8]. To stabilize the debris field in LEO, an estimated five ADR missions per year will be required, beginning in the next few decades, in addition to mitigation strategies. However, even this would not end major collisions in LEO, and additional ADR missions would be needed to go beyond stabilization and begin to reduce the LEO debris field.

Notwithstanding the significant legal, political, and financial obstacles, ADR presents a number of difficult engineering challenges. These include the lack of traditional docking/grasping fixtures on the debris, their non-cooperative nature, limited knowledge of their structural health and spin characteristics, and the significant ΔV needed for controlled deorbits. Thus, a major ADR mission has never been attempted, though some are in development [9]. The first ADR efforts will require the validation of many new technologies in proximity operations and space robotics, in addition to new observational data on potential targets.

Sweeps of high-priority debris reveal a number of appealing initial targets for removal. In particular, there are nearly 2,000 spent upper-stage rocket bodies (R/Bs) in LEO, many of which are clustered into crowded altitude-inclination bands. They have a relatively simple geometry and for a given R/B model, many are available for removal. For example, there are 288 COSMOS-3M second stages in LEO clustered into four well-defined bands and having a mass around 1400 kg, a diameter of 2.4 m, and a length of 6.5 m. The 22 Zenit-2 second stages in LEO are also important targets due to their unusually high mass of 9000 kg. In both cases, many of the remaining R/Bs are in orbits above 800 km and would take centuries to naturally decay through atmospheric drag.

Many proposals have been offered for capture of large debris such as R/Bs, including using nets [10], tethered harpoons [11], various forms of adhesion [12, 13], mechanical grippers [14], grapples [15], or tentacles [16]. However, each has significant technical gaps that need to be resolved. Initial attachment to the R/B and the subsequent stabilization are two of the most difficult phases of the operation, and accomplishing both may require new concepts and technologies.

Accordingly, the main contributions of this paper are as follows: (1) Investigation of a new approach using controllable dry adhesives (CDAs) to dock to and stabilize tumbling R/B debris, and (2) an exploration of possible roles for CDAs in thruster attachment and during deorbit burns.

2. Controllable Dry Adhesives

There has been a great deal of recent interest in controllable dry adhesives (CDAs) for a variety of space applications, such as robotic satellite servicing, rendezvous and docking, and orbital debris removal [17]. CDAs take inspiration from the adhesive capability of the feet of gecko lizards. They are produced by covering a pad with flexible microstructures which can bend and conform to smooth or lightly textured surfaces that they are pressed against. This creates an unusually high amount of contact area between the surface and the pad, which activates adhesion driven purely through van der Waals forces.

Thus, CDAs are classified as "dry" adhesion, which has many advantages over "wet" chemical adhesion in space applications. In particular, many chemical adhesives do not function in extreme temperatures and are susceptible to outgassing in the vacuum of space, which may contaminate optical sensors and cause other undesirable effects. Even chemical adhesives which overcome these difficulties require

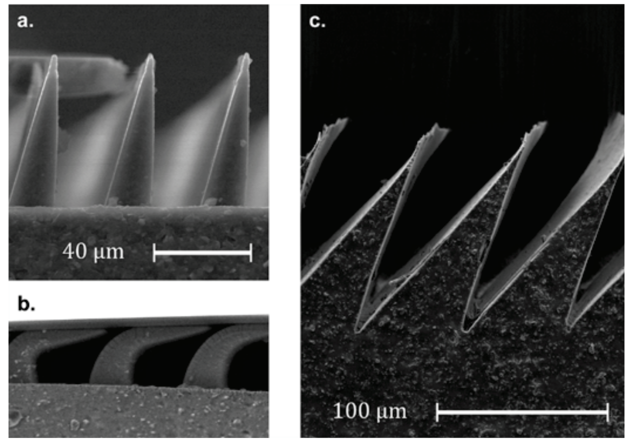

Figure 1. (a) In wedge-type CDAs, micro-wedges manufactured from elastic material rest nominally in an upright position. (b) When pressed against a surface in shear, the wedges bend to create a large amount of contact area, producing adhesion. (c) Wedge angle can be modified to produce directionality in the shear needed to engage the adhesion.

a long curing process of up to several hours, limiting their use as the primary means of attachment to dynamic objects. In contrast, CDAs can be manufactured using space-qualified polymers, with experiments showing continued performance and high durability under extreme temperatures, doses of radiation, and in a vacuum, without outgassing [18].

In addition, CDAs are considered "controllable" because the adhesion can be rapidly and reliably activated and deactivated. This is because for certain configurations of microstructures (e.g. Fig. 1), the adhesion is only engaged when forces between the adhesive pad and the surface are applied in a particular preferred direction. For example, CDAs currently undergoing tests on the ISS and at NASA JPL activate when in contact and given a small amount of shear force in a certain direction. When this force is removed, the pad undergoes rapid and clean detachment. Thus, CDAs are reusable and have been shown to undergo thousands of cycles with minimal degradation of performance.

Early CDAs were printed on flat rigid pads to enable adhesion to flat surfaces. More recently, CDAs have been printed on flexible thin films, allowing them to conform and attach to curved surfaces [19]. Recent experiments have shown that these can be used to produce grippers capable of dynamic grasping of curved, spinning objects with high robustness to varying contact conditions including position and angle misalignments [20]. This offers a much wider space for microgravity grasping and manipulation compared to traditional robotic manipulators, which are often limited to attaching to special grasping fixtures and require a high-precision grasp maneuver for success, difficult to achieve on a dynamic target.

Adhesive strength is also important to dynamic grasping and subsequent manipulation. Recent CDAs show maximum adhesive stress of up to 90 kPa in the preferred shear direction and 25 kPa in the normal direction on glass surfaces. This stress rating depends on surface roughness and the geometry of the adhesive microstructures. However, total adhesive strength depends on the housing gripper's ability to tension the CDA films so as to increase engagement of the adhesive across their entire surface area. Investigations into load-distributing gripper architectures have shown that CDA grippers can be efficiently scaled up to hold very high loads [21]. Such strength will be required for docking and deorbiting of massive R/Bs.

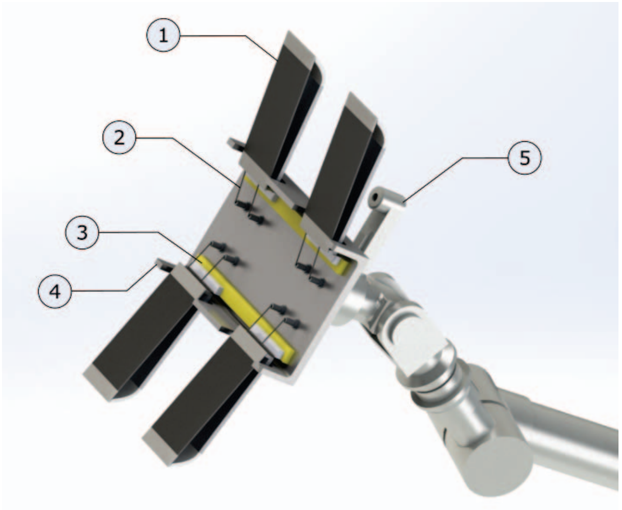

Figure 2. Conceptual model showing potential features of a CDA gripper for curved surfaces, including (1) thin, flexible CDA films, (2) cables to apply tension to the films, activating the adhesion, (3) a damping elements to avoid rigid attachment between the gripper frame and the CDA fingers, (4) extensions of the gripper frame which contact the target surface and carry compressive loads, and (5) an optical camera for tracking the target surface. Also shown are elements of the wrist mechanism, including a spin table.

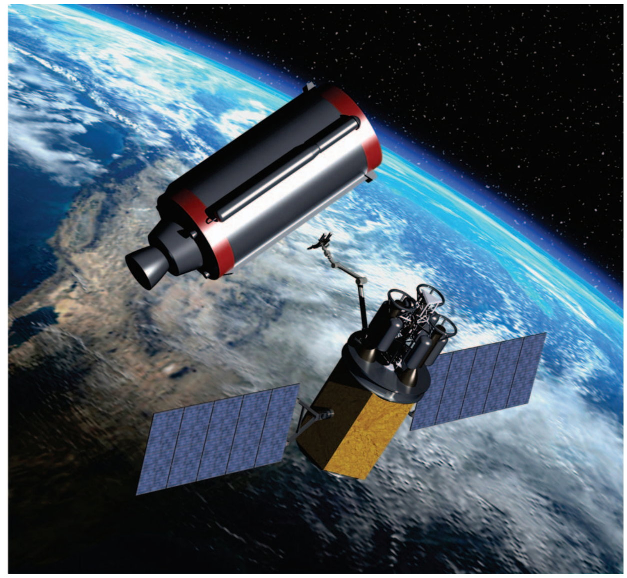

Figure 3. To-scale visualization of a chaser spacecraft approaching a tumbling rocket body debris target using a CDA gripper arm.

3. Approach and Docking Maneuver

Initial docking is one of the most difficult phases of an ADR mission to a R/B. For one thing, each R/B object is an uncontrolled, non-cooperative target having residual spin, potentially about multiple geometric axes. Upper stage R/Bs receive their initial spin from the kickback of releasing their payload into orbit, as well as subsequent outgassing. Studies have shown that due to internal damping and external disturbances, such as the atmosphere and Earth's magnetic field, the spin is expected to decay, leaving a final spin primarily about the largest principal axis of inertia. Indeed, some information can be gathered from optical ground observation data, which seems to verify that spin rate decays significantly over the course of a few years [22]. However, much is still unknown which would have implications for the type of approach needed. For example, residual spin about the axial axis is difficult to measure from ground observations. This axial spin could lead to a geometric coning effect as shown in Fig. 4, complicating the docking approach. In addition, geometric models of the R/Bs may be incomplete, and parts of the structure may be damaged by debris impacts and accidental explosions caused by overpressurizing due to unused fuel.

Another difficulty arises from the lack of fixtures designed for traditional docking or robotic grasping. For docking proposals, one common candidate for a grasping/grappling fixture is the main rocket nozzle. Using traditional methods, docking with the nozzle requires chasing the end of the R/B as it tumbles, matching its spin in order to minimize relative velocity and achieve a precise mechanical engagement. Such a maneuver is high-risk, time-sensitive, and difficult to plan and execute. High spin rate and multi-axis spin may make this maneuver infeasible, particularly for large chaser spacecraft. In addition, given the highly dynamic shadowing and the absence of features designed as visual cues on the tumbling R/B, it is unclear what sensor suite could guide such a maneuver. Indeed, many such approaches include a "point of no return," after which erratic spin of the R/B could lead to catastrophic failure, producing additional orbital debris.

Description of Proposed Maneuver

Facing these challenges, the unique capabilities of CDA grippers may offer new approach and docking concepts. One such concept, described here, consists of four phases:

1. Rendezvous and observation: First, a target should be chosen which has had time to outgas residual fuel in unstable tanks and reach a steady-state spin rate. Observations of R/Bs suggest that could take many years [23], but many appealing targets have indeed been in orbit for decades. Before launch, ground observations of the target R/B should be made, which can be used to estimate the direction of the angular momentum axis [24, 25]. For optimal lighting conditions illuminating the curved surface of the R/B shell, the launch date should be timed such that the R/B angular momentum vector has a large component pointed toward the sun. Standard mission planning techniques can then be used for far-field and near-field rendezvous.

After rendezvous with the target to within tens of meters, an observation period begins, whereby optical data is taken and sent to a ground station to identify the spin characteristics and revise a geometric model of the R/B. In particular, one may search for previously unknown modifications to the particular R/B, as well as large damage from debris impacts and fuel tank ruptures. In addition, mission controllers will estimate the location of the center of mass and take note of spin disturbances which may indicate unused fuel sloshing in the R/B tanks.

2. Proximity operations approach: With this information in hand, the chaser will begin its approach towards the R/B center of mass. To avoid contact with the tumbling body, an inertial approach will be required along the angular momentum axis. Once the R/B is within range for grasping, the chaser will stabilize its relative position to the R/B, ensuring that it is well outside the geometric cones traced by any R/B multi-axis spin. Maintaining this relative station keeping will require a small amount of fuel expenditure, though this will be negligible compared to the fuel used for rendezvous [26]. Prudent timing of the thrusters may be needed to avoid plume impingement with the tumbling target.

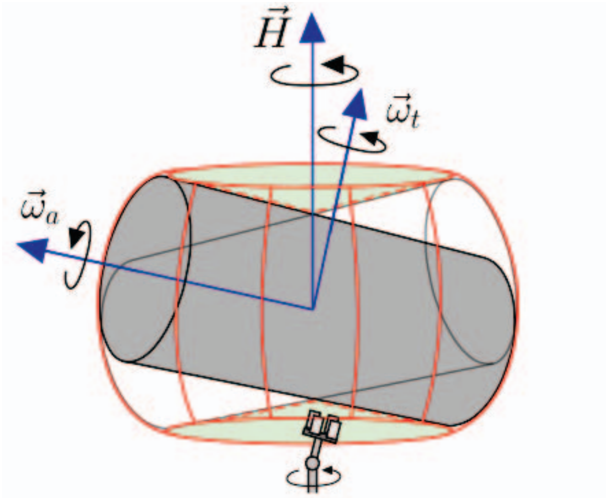

Figure 4. Residual spin about the axial axis of the rocket body ($\vec{\omega}_a$) coupled with the main transverse spin ($\vec{\omega}_t$) can produce a coning effect, leaving conical collision-free regions (shown in green) in which the robot arm can safely maneuver (figure is not to scale). The arm can then be spun up to reduce relative motion with the R/B surface.

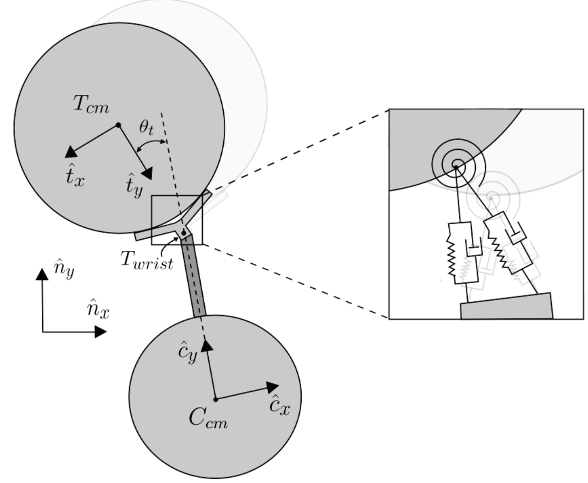

Figure 5. Planar model used in simulation, with a close-up revealing translational and rotational springs and dampers used to model the behavior of a compliant wrist.

3. Robotic arm initial reach: The chaser will be equipped with a sturdy robotic arm terminating in a CDA gripper. The arm mechanism will include several key components in series: (1) a spin table, a feature which has been included in previous capture proposals [27], (2) a revolute joint, and (3) a wrist having some compliance, potentially in multiple degrees of freedom. For sensing, an optical camera will also be mounted on the wrist. The gripper will be extended toward the R/B along its angular momentum axis, stopping outside any regions of potential collision. Here, the geometric coning may play a role. To provide some intuition, for an axially symmetric body, the half-angle β of the relevant cone will be given by

$$\beta = \tan^{-1}(H_a/H_t) \tag{1}$$

where H_a and H_t are the angular momentum about the axial and transverse axes, respectively. For a uniform cylinder of the dimensions of a COSMOS-3M rocket body, $\omega_a = 2°/s$ and $\omega_t = 10°/s$ would result in $\beta = 85°$, potentially significant for the final attachment. To remedy this, in the case of geometric coning, the revolute joint can adjust to match the half angle of the cone. The spin table will then be spun up until the camera rotational motion is minimized, effectively aligning the gripper with the R/B surface. At this point, a final observation phase will begin. The motion of obstacles on the surface such as exterior piping will be noted, in addition to potentially damaging micrometeoroid craters that could not be previously seen. Finally, a promising location on the surface for the final attachment will be decided by the mission controllers.

4. Final arm extension and attachment: Following a designed timing plan, the arm will conduct a final rapid extension to contact the R/B, avoiding previously characterized dynamic obstacles. The wrist compliance will allow final gripper pose adjustments to engage the gripper in a secure grasp of the R/B surface. Compliance and damping in the robotic arm mechanism will allow angular momentum to be gradually transferred to the chaser spacecraft, eventually eliminating any relative rotation. At this point the joints of the robotic arm will be rigidized to prepare for a controlled stabilization of the chaser/spacecraft system.

A docking maneuver of this sort has many benefits, including its low-risk nature, having few time-sensitive elements. Ample time is available to take new measurements, build a feature map for optical range-finding, and gather new relevant data for replanning, and there are many opportunities to abort, even up to the final extension of the robotic arm. In addition, very little maneuvering fuel is required compared to other more intensive maneuvers. A maneuver of this sort could also conceivably be attempted using flexible electroadhesives. However, electroadhesives require continuous activation to maintain their adhesion. On the other hand, CDA grippers, once engaged, can passively stay engaged until active detachment. Thus, CDAs appear to be uniquely qualified to enable such an approach.

Another major advantage is that this approach offers the possibility a very low impulse attachment, in spite of the tumble of the R/B. In the case that R/B spin is fully about the transverse axis, the spin table can eliminate relative motion between the gripper and a docking surface on the R/B exterior. Moments experienced in matching the spin of the chaser and R/B can then be fully controlled by the spin table. However, though transverse spin is expected to dominate, a small amount of residual axial spin may exist due to insufficient time for spin decay, external disturbances, and misalignment between the transverse axis and the largest principal axis of inertia. This can actually be beneficial for attachment, since it has been shown that axial spin can be leveraged by CDA grippers for a more robust initial grasp [20]. On the other hand, using the proposed approach, axial spin makes indefinitely eliminating relative motion impossible, and thus reaction forces and moments after attachment are guaranteed.

Numerical Simulation

These concerns motivate an investigation of the forces experienced on contact with an R/B having some residual axial spin. Through numerical simulations of a planar model depicted in Fig. 5, we determined the forces and moments the CDA gripper must exert during the attachment phase. For a dynamic model, we assumed a target R/B of comparable size to a COSMOS-3M second stage, having a diameter of 2.4 m and mass of 1400 kg. The diameter of the chaser and length of the robot arm were both chosen as 2 m, and the mass of the chaser was set to 1700 kg. Recent ground observations have shown COSMOS objects having a transverse spin of $9°/s$ [24],

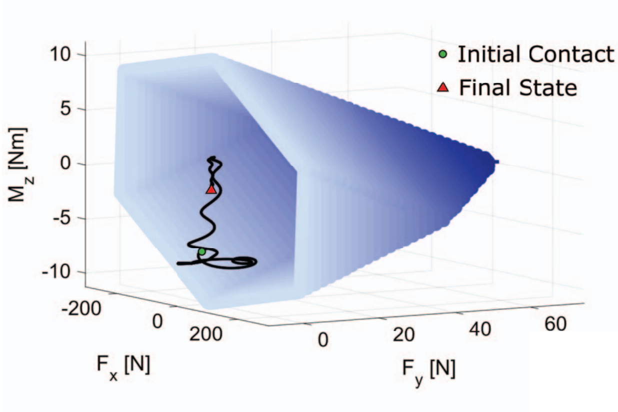

Figure 6. Trajectory of forces and moments generated during simulation is shown to remain inside the adhesion limit surface. Compressive forces ($F_y < 0$) occur which load the structure of the wrist rather than the adhesive capabilities. The shading from light to dark indicates small to large normal forces and is used to highlight the 3D shape of the surface.

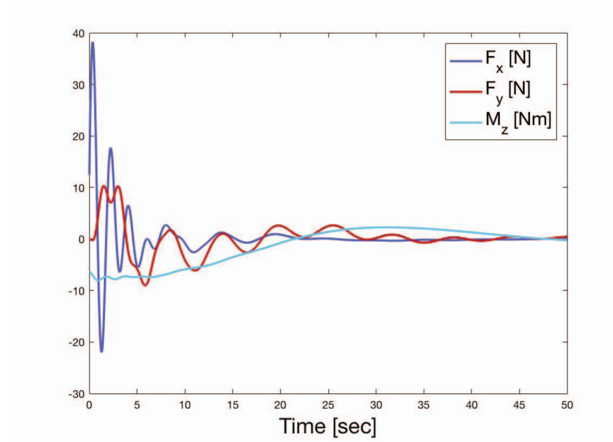

Figure 7. Components of the forces generated at T_{wrist} in the $\hat{t}_x$ and $\hat{t}_y$ directions (F_x and F_y), as well as the moment generated on the target R/B about T_{wrist} in the $\hat{t}_z$ direction (M_z).

and axial spin is expected to be much less [22]. However, for conservatism, we set $6°/s$ as the initial axial spin of the R/B.

In accordance with our mission concept, we assumed zero initial approach velocity. We also assumed an initial contact state having the position vector from C_{cm} to T_{cm} parallel to $\hat{c}_y$. This means that the contact point on the chaser will be in the center of the gripper. However, as shown in [20], for the case of a rotating target object, it can often be beneficial to impact the target with some nonzero offset from the center. In practice, the robotic arm mechanism can exploit this to ensure that the highly robust approach conditions are used. The model also considered the chaser spacecraft and robotic arm to be a single free-floating rigid body. In practice, there will be at least one joint in the robotic arm. As explored in [28], free joints in the robotic arm can help minimize the impulse felt at the contact point. Thus, our model adds some additional conservatism.

We modeled a passive compliant wrist using a series of springs and dampers (linear and torsional). For generality, the pivot point of the wrist (T_{wrist}) was assumed to be on the surface of the target (this point would be slightly offset from the surface in a real gripper). We tuned the springs and dampers to meet two specifications: constraining the resulting range of motion for each axis while staying within the adhesive limits of the CDAs. The variables we considered for the range of motion were the angle between the chaser-fixed basis c and the target-fixed basis t ($\delta\theta_t$), the deflection of T_{wrist} in the $\hat{c}_x$ direction (δx_t), and the deflection of T_{wrist} in the $\hat{c}_y$ direction (δy_t). The maximum values observed in simulation were $\delta\theta_t = 33°$, δx_t = 3.1 cm, and δy_t = 1.9 cm. These are comparable to values observed in hardware testing of a CDA gripper in [29].

The authors in [29] explore the limitations of CDAs when applied to curved surface grippers. Given the radius of the target body, the geometry of the gripper, and the maximum shear force the adhesive pads can tolerate, they solve a series of optimization problems to determine the set of force and moment combinations that the CDAs can apply at the limit of their adhesive capabilities. These optimization problems generate a convex limit surface in force/moment space. In Fig. 6 we plot this surface for a gripper having four adhesive pads, each having an area of 200 cm^2, with a 30 cm gap between opposing adhesive pads as shown in see Fig. 2. We assume the surface material of the target is bare aluminum, resulting in a shear adhesive pressure of 50 kPa. We then plot the results of our simulation in this space, showing that the force/moment trajectory always remains within the adhesive limits of the CDA. There are a few regions in which the gripper is loaded in compression—however, this loads the structure of the gripper rather than the adhesives. Since this limit surface was generated for adhesive rather than structural limits, the limit surface does not extend into the compression region ($F_y < 0$). However, at a peak compressive force of 9 N, as seen in Fig. 7, we do not expect the structure to be overly strained.

It is possible that future deorbiting targets may include R/Bs which are larger than the COSMOS-3M or whose spin rates have not decayed below the investigated level. In this case, it is simple to expand the limit surface in Fig. 6. This could be done by increasing the size of the adhesive pads or adjusting the geometry of the gripper. A wider gripper having more space between the two sets of pads can also significantly increase the size of the limit surface along the M_z axis.

4. STABILIZATION PHASE

Many ideas have been proposed for removing the residual spin and stabilizing R/B debris for deorbit. Such concepts include attaching yo-yo despin packages, gravity gradient booms, or electromagnetic stabilization kits [27]. Each of these require an initial rigid attachment to install. Concepts not requiring initial attachment include contactless methods such as ion beam impingement, which has been proposed not only for stabilization but for the full deorbit operation [30].

Other concepts eliminate rigid attachment and stabilization altogether, e.g. by arresting the R/B using nets or harpoons, where deorbit would be accomplished by dragging the R/B using a tether. Such approaches have difficulties such as ensuring successful attachment and limiting additional fuel usage during ongoing stabilizing control of the coupled system. More serious are potential collisions with the R/B if the tether becomes tangled or cannot remain taut (e.g. between burns in a multi-burn deorbit plan) or if tether mechanisms such as the reel fail. Since avoiding generation of additional debris is of primary importance in an ADR mission, more tether concept validation missions will be needed before being applied in such a risky scenario. However, recent simulations and parabolic flight experiments have shown promise that this may eventually be feasible [11].

In any case, once rigid attachment is made between the chaser and the R/B, as when using CDA grippers, stabilization using chaser thrusters is a quick and simple solution. However, the point of attachment near the center of mass is not an ideal place for using thrusters to reduce spin. Here, the robotic arm works to an additional advantage and can be extended to increase the moment arm about various axes, minimizing fuel usage for the despin. Simulations have shown that even for a large R/B, stabilization can be completed in a few seconds [27]. In addition the forces experienced by the CDAs during this phase can be carefully controlled and are minimal compared to the docking phase.

5. Thruster Attachment and Deorbit

Since large fragments of R/B debris are expected to remain intact after reentry, reliable deorbit into the ocean or unpopulated areas is imperative. Following previously established operating standards, ESA and the U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP) specify that the risk of human casualty must be less than 1 in 10,000 for debris removal [31]. These stringent safety standards may rule out deorbit concepts that are more "gradual" such as drag-enhancing methods and ion propulsion/impingement, since they do not have sufficient control over the reentry location.

Hybrid rocket engines are a good fit for this application since they have a high specific impulse, relatively small size/weight, and are throttleable and restartable, though the technology requires further development. Furthermore, the structural integrity of R/B debris is unknown, and they may buckle under the high thrust forces produced by solid rocket engines. Thus, a multiple-burn plan using moderate thrusts may be the best solution—well-suited for a hybrid engine. A hybrid engine module on the order of 200 kg can be expected for deorbiting a 1400 kg COSMOS-3M R/B from an 800 km altitude [15].

Once the chaser is attached and the R/B is stabilized using the CDA gripper, there are two potential strategies for performing the deorbit burn: (1) using engines directly on the chaser spacecraft (i.e. sacrificial), or (2) fixing independent deorbit engine modules to the R/B. The latter option allows the chaser spacecraft to carry multiple deorbit modules and visit many R/Bs, ultimately making the mission more cost-effective. Indeed, the chaser could conceivably be refueled and equipped with additional deorbit kits on orbit for further reuse.

In this scheme, the chaser must first attach the deorbit modules securely to the chassis of the R/B. Previous studies have considered various approaches for mechanically fastening the deorbit modules to the primary nozzle of the R/B, including traditional clamps and grapples [14, 15, 32]. The primary nozzle is generally believed to be the most structurally sound part of the R/B and offers more cageable features (e.g. the rim of the nozzle or the plenum). However, the unique capabilities of CDA grippers allow for other potential *surface-mounted* configurations. We consider three notional configurations in which the deorbit modules can be arranged (see Fig. 8). Note that although each module would be equipped with RCS micro-thrusters for attitude adjustments, the primary thrust vector must be closely aligned with the R/B's mass center for efficient burns.

A. *Axis-aligned nozzle mounting*: If the interior surface of the nozzle is amenable to adhesion, a mounting ring lined by CDA material can be inserted into the nozzle until it is firmly pressed against the interior on all sides. By mounting the CDA on a deformable material such that its adhesive direction points out of the nozzle, it can conform to surface curvature within the nozzle and resist removal. A system of this sort could conform to a variety of nozzle sizes and curvatures.

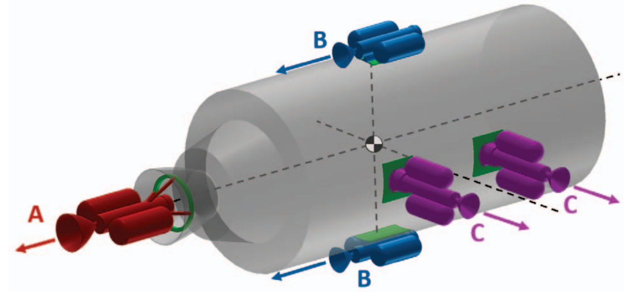

Figure 8. Three configurations of deorbit modules attached to the rocket body using CDAs: (A) Axis-aligned nozzle mounting, (B) Axis-aligned side mounting, and (C) Radially-aligned side mounting. Surfaces coated in CDAs are indicated in green, and arrows point in the direction of exhaust.

B. *Axis-aligned side mounting*: Utilizing the shear-induced adhesive properties of CDAs, another possible mounting configuration is to place two modules on opposing sides of the main shell such that they are aligned with the primary axis. While this configuration does require two modules (to create zero net moment), its location near the initial docking position may make them easier to install. In this case, the modules transfer all thrust through shear forces on the CDA. For hybrid rocket thrust of 4 kN attached to bare alumnimum, an adhesive pad size less than 0.1 m^2 would be required for each module.

C. *Radially-aligned side mounting*: Another convenient mounting configuration is to place two modules pointing radially inward on the shell. While only one module is required if the location of the mass center is known precisely, even a small uncertainty in the location of the mass center would cause the primary thruster to induce a large moment, and thus heavily tax or saturate the RCS thrusters. Therefore, two thrusters are more robust to mass uncertainties. However, it is unclear that the exterior shell of a given R/B can handle high radial thrust loads.

Any approach involving independent deorbit modules requires that the chaser spacecraft deposit them securely onto the R/B. Since the proposed initial grasping site for the chaser is near the mass center, placing side-mounted deorbit modules (i.e. B and C in Fig. 8) may only require a separate robotic arm for manipulating them into position. On the other hand, nozzle-mounted deorbit modules are farther from the chaser attachment site and may require the chaser to crawl along the R/B shell to get into position, another unique capability potentially enabled by CDA grippers. For a stabilized chaser/target system, such a crawling maneuver could conceivably be accomplished using a single gripper, since CDA grippers can controllably detach without imparting reaction forces to the grasped object. However, such a maneuver may add unacceptable risk, which may motivate modifications to the gripper design or the addition of a second CDA gripper arm.

6. Summary

This paper proposes a number of concepts for applying CDAs to the challenging problem of reliable R/B debris deorbiting.

Though CDAs grippers offer new alternatives for low-risk and low-impulse docking, residual axial spin of the R/B can cause unavoidable reaction forces and moments. We showed through simulation that these are expected to be well within the capabilities of CDA grippers. In addition, the robot arm needed for this concept can be exploited for better stabilization and potential attachment of deorbiting kits using traditional grasping/grappling methods or CDAs.

There are several remaining challenges for CDAs that warrant further study. A significant issue may be the corrosion of materials in LEO due to high-velocity atomic oxygen (AO). Experiments on the Long Duration Exposure Facility and the ISS have shown that over the course of a few years, AO can erode a wide variety of commonly used materials and coatings [33]. This may increase surface roughness or leave a loosely attached film of oxidized material, reducing adhesion effectiveness [34]. Many high-priority R/Bs are particularly susceptible to this issue since they have remained in LEO for decades and their tumble exposes every part of their exterior to the AO wind. Such long-duration exposure, coupled with small debris impacts and thermal cycles, may even compromise the structural integrity of the exterior shell, eliminating it as a final attachment point for deorbit thrusters. On the other hand, metals are some of the least susceptible materials to AO corrosion [35]. Indeed, aluminum is particularly resistant and forms the shell structure of most R/B debris targets. Thus, extremely long duration exposure may provide the benefit of paint and anodized coatings being completely eroded, leaving a rough aluminum surface more amenable to adhesion. Experiments using CDAs on AO-corroded samples will be needed to characterize the reduction in adhesive strength due to this surface roughness.

Additional future work may include design of components needed for a space-qualified CDA gripper and compliant wrist mechanism, 6-DOF experimental tests of the proposed docking maneuver, and additional characterization of CDA grippers in dynamic contact and loading conditions in more degrees of freedom. Manufacturing methods currently under development for CDA films allow modifying microwedge geometry and directionality across a single film, further expanding the safe envelopes for robust grasp and continued adhesion under various loads.

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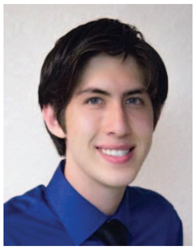
BIOGRAPHY



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