Gecko-Inspired Adhesive Lasso for De-tumbling Orbital Debris

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***Abstract*— For non-destructive orbital debris capture, de-tumbling is often a necessary step. However, gaining control of objects that are large and rotating with an irregular or unpredictable trajectory is challenging. We present a concept and initial experiments aimed at establishing the feasibility of restraining such objects using a gecko-inspired adhesive attached to a tether: *Gecko Lasso*. We assume that the adhesive is brought into initial contact by an acquisition vehicle using a lightweight arm or extendable boom. As the object rotates, it wraps the tether around itself, rapidly increasing the maximum permissible tether tension. Experiments with rotating metal cylinders and a small sample of adhesive indicate that gentle attachment is possible for fast-moving targets; tangential velocities up to $1.3\ \mathrm{m\,s^{-1}}$ were tested with a 90% success rate. We conclude with a discussion of extensions to take this new concept to the next level of technology readiness.**

I. Introduction

Orbital debris in scientifically and commercially useful orbits has been a growing problem for decades, leading to a collisional cascading effect known as the Kessler Syndrome [1], [2]. Due to many recent and planned deployments of satellite constellations, the number of satellites in orbit has surpassed an unstable or runaway threshold at many altitudes [3]. Left unchecked, existing and future debris will pose a serious threat to near-Earth activities. Large debris must be removed to maintain or improve the safety of the current low Earth orbit (LEO) environment [4], [5], highlighting the need for the continued development of active debris removal (ADR) technologies. In this work, we introduce *Gecko Lasso,* which employs a small, flexible, gecko-inspired adhesive patch affixed to a tension-controlled tether to contact, de-tumble, and ultimately capture debris (see fig. 1).

II. Related work

A. Debris stabilization and capture

Existing ADR methods [6] can largely be categorized into two groups: contact-based and contactless. In this work, we focus on contact-based methods due to their potential for extension to a variety of use cases, including capture and manipulation for refurbishing or recycling components. These methods have proven challenging, in large part due to the requirement for close-range maneuvering with target objects that may be rotating or tumbling [7].

Knowledge of target debris parameters such as attitude and spin axis orientation may enable autonomous rendezvous

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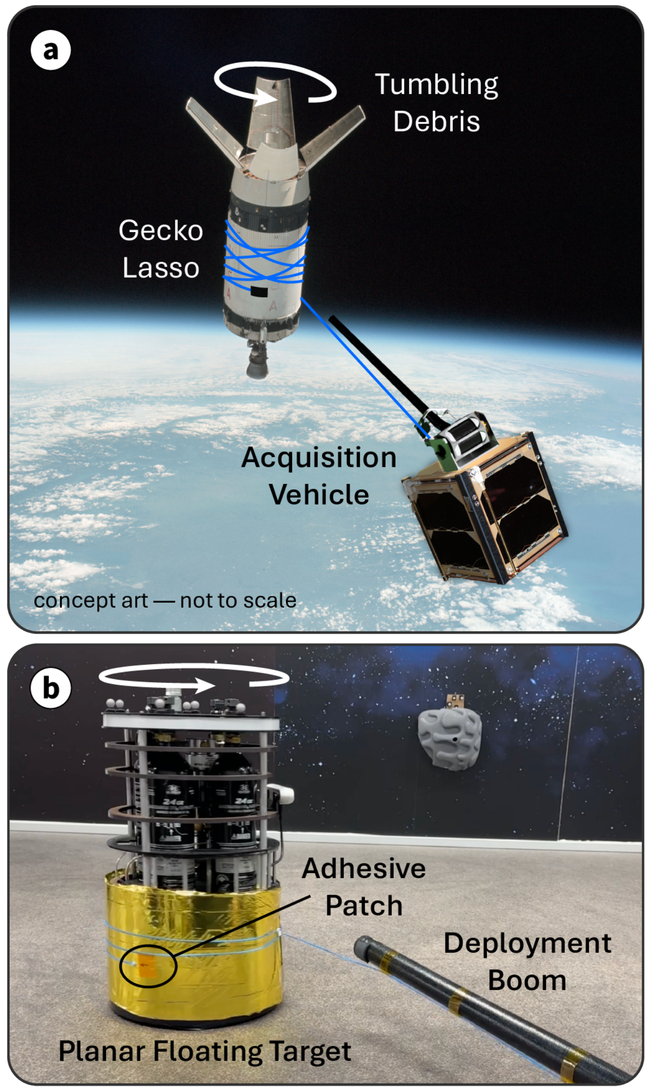

Fig. 1. Concept (a) of capturing a rotating object using an adhesive lasso, with a small patch of film-backed gecko-inspired adhesive attached to a tether (not to scale). The adhesive is brought into contact using a lightweight arm or boom. After contact, the tether wraps around the object, increasing the maximum applicable tension by exploiting the capstan effect. Planar approximation (b) using a floating robot on an air bearing, a fiberglass boom, and a patch of adhesive on a tether (video included in multimedia materials).

with tumbling objects through careful trajectory planning [8]. These parameters can be measured using photometric [9]–[11] or vision [12] techniques. Targets with angular velocities of up to $1.25\ \mathrm{rad\,s^{-1}}$ in LEO and $7\ \mathrm{rad\,s^{-1}}$ in geostationary orbit (GEO) have been reported [9]. Despite the availability of target parameter measurements, non-cooperative or fast-moving objects are still challenging to approach, making de-tumbling necessary for successful capture.

Several contact-based de-tumbling strategies have been proposed in the literature:

- *Friction* using brushes [13] or flexible rods [14] can slow debris through controlled contact, and has been proposed for targets rotating at speeds from $0.05\ \mathrm{rad\,s^{-1}}$ to $0.5\ \mathrm{rad\,s^{-1}}$. The approach does not depend on the target object's size or mass but does require the acquisition vehicle (AV) to maintain close, controlled contact. It does not result in a mechanical connection.
- *Rigid Contact* with robot arms and grippers has been proposed but again faces challenges with increasing object size, unless the object is provided with favorable gripping features. Researchers have reported target dynamics as a limiting factor in successful de-tumbling, requiring relatively slow angular velocities of $0.17\ \mathrm{rad\,s^{-1}}$ or less [15]–[17].
- *Nets and tethers* have been proposed to enclose and subsequently de-orbit debris [18]–[21], though this approach becomes more challenging and requires a larger AV as target size increases.

B. Gecko-inspired adhesives in space

To successfully utilize contact-based de-tumbling methods, secure initial contact must be made with tumbling targets. Gecko-inspired adhesives, particularly anisotropic adhesives, have been proposed for a number of gripping and attachment applications in space. Examples include grippers for flat surfaces that take advantage of opposed rigid adhesive tiles [22], [23] and curved surface grippers that use thin-film adhesives to conform to targets [24]–[26]. In planar experiments, thin-film grippers demonstrated an ability to grasp slowly rotating targets with a diameter of up to approximately $5\times$ the gripper size [27]. When compared to other capture or de-tumbling methods, the use of gecko-inspired adhesives stands out due to their ability to attach gently, with very little preload force, which reduces the chance of disturbing the object's trajectory. They also do not require external power to engage or remain attached.

Anisotropic gecko-inspired adhesives are made from silicones such as *Sylgard 170* and are micro-patterned to leverage van der Waals forces and adhere to smooth surfaces (fig. 2). Initially, only the tips of the sharp, wedge-shaped microscopic features make contact with the object surface, requiring a very small normal pressure. At this stage the real area of contact is small and adhesion is negligible. Upon the addition of a shear loading force along the microstructure's preferred direction (fig. 2b), the wedges bend and the area of contact grows, becoming almost continuous.

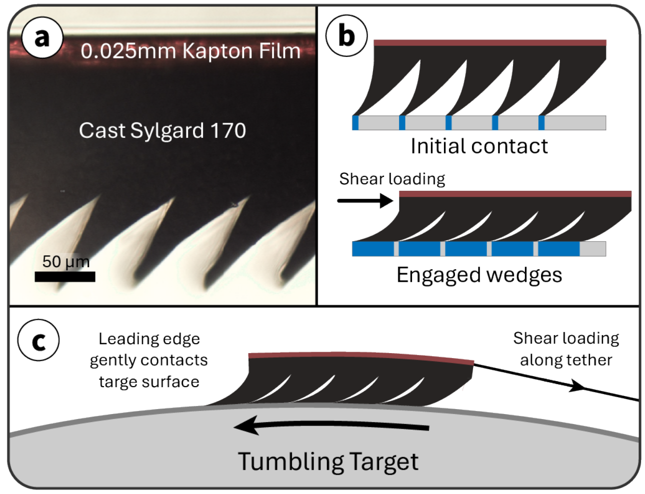

Fig. 2. Anisotropic adhesive geometry (a) and engagement details (b). Shear loading engages microscopic wedge structures, greatly increasing the contact area, shown in blue. A flexible Kapton backing allows adhesive to conform to curved target surfaces. The adhesive is loaded in shear through tension on the lasso's tether (c). Diagram not to scale (target radius $\approx h \times 10^4$, where h is adhesive thickness).

In this condition, anisotropic gecko-inspired adhesives can typically sustain shear stresses of up to $90\ \mathrm{kPa}$ and normal stresses of up to $20\ \mathrm{kPa}$. The adhesion is strongest when applied to smooth surfaces, though modest variations in surface texture can be tolerated.

Other work has tested adhesives in space conditions including exposure to vacuum [28]–[30], alpha and gamma radiation [31], [32], extreme temperatures [33]–[37], and microgravity [23], [24], [38], suggesting that gecko-inspired adhesive performance can persist for some time in the harsh environment of space.

C. Contributions

As noted above, gecko-inspired adhesives have demonstrated their potential for use in space. However, there remains the challenge of initial grasp when de-tumbling large, rotating objects. Here, we introduce mathematical constraints on the gentle attachment of gecko-inspired adhesives to tumbling targets and perform a simple experiment to begin addressing the question: *Under what range of conditions will tethered adhesives attach to a spinning surface?*

III. Gecko Lasso Operation and Design

The goal of Gecko Lasso is to gently attach to, tether, and control target debris. The basic concept of operations is shown in fig. 3.

We assume that an AV wishes to capture a target. The AV has thrusters and is equipped with an extendable arm or boom. At the tip of this boom is a patch of gecko-inspired adhesive, which is gently supported from behind with a compliant suspension and connected to the AV through a tether controlled by a winch. The target is an object in orbit that has a primary axis of rotation, z, although it may also have some wobble and a slow rate of rotation about an

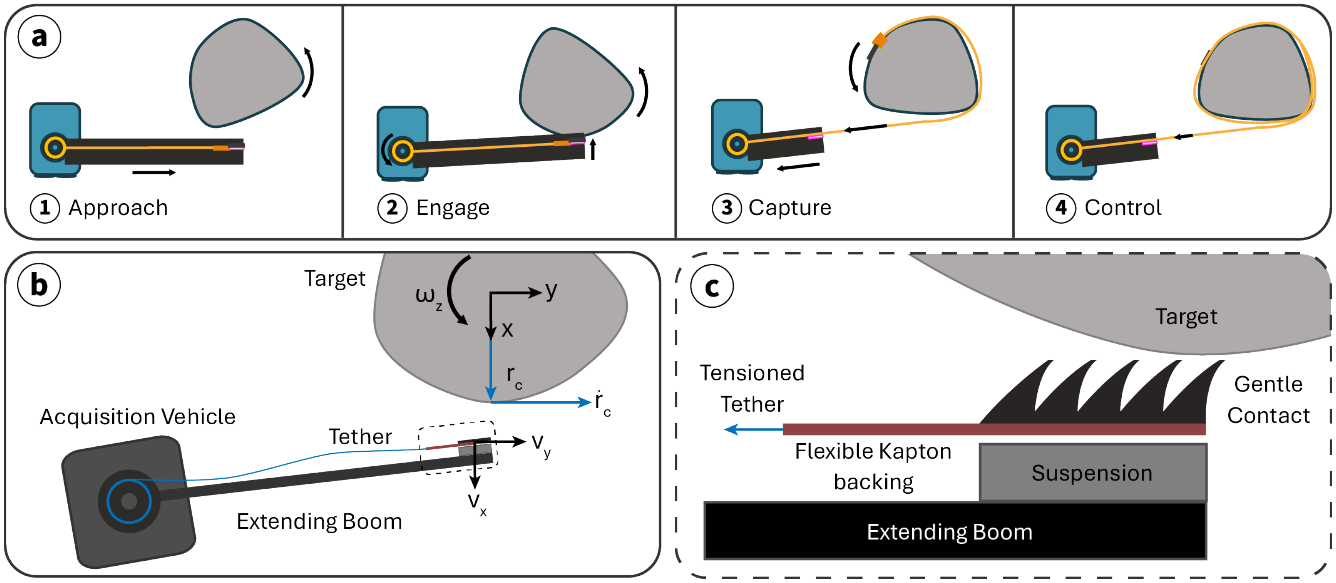

Fig. 3. Schematic and coordinate definitions for a gecko adhesive patch approaching and contacting a rotating object. The concept of operations in which (1) an extendable boom lengthens towards the target, (2) gently touches the Gecko Lasso to the target surface to engage the adhesive, (3) wraps a tether around the target, and (4) controls tether tension to slow the tumbling target is shown in (a). A diagram detailing the coordinate frames defined in this work is shown in (b). A closeup diagram of the Gecko Lasso adhesive patch is shown in (c) (wedge microstructure not to scale).

orthogonal axis. For the purposes of this paper, we assume that rotations other than ω_z are negligible.

The AV orients itself nominally orthogonal to the target axis of rotation such that the desired contact location is rotating "away" from the AV and extends a boom toward it, gently contacting the outer surface. As soon as the adhesive engages, it becomes affixed to the target object, connected to the AV by the tether. Once attached, the AV may apply tension to the tether and start to reduce the target object rotation.

In the next section we define the coordinates, velocities, and constraints that govern adhesive success or failure for a planar idealization of the adhesive capture problem.

A. Problem Statement

Of the various parameters that ultimately may affect the success of the Gecko Lasso concept, we focus here on the dynamics of initial attachment. To provide theoretical insight into the constraints, we consider the simplified case of an object rotating about a single axis.

We embed a coordinate frame in the target, with z along the axis of rotation and the x axis pointing toward the initial contact site. The adhesive patch is small in comparison to the target (not drawn to scale in fig. 3a) and we therefore treat the patch as a particle. The relative velocity of the patch with respect to the target is $\mathbf{v}_0 = [v_x, v_y, 0]^T$. The contact site has the location $\mathbf{r_c} = [r, 0, 0]^T$ in the target coordinate frame and is moving with an instantaneous velocity $\delta\mathbf{r_c}/\delta t = [0, \omega_z r, 0]^T$. The acceleration to which the patch will be subjected during engagement is:

$$\mathbf{a_c} = \begin{bmatrix} -v_x \\ \omega_z r - v_y \\ 0 \end{bmatrix} \cdot \frac{1}{\delta t} \tag{1}$$

where δt is the time taken for the adhesive to engage.

In general, v_x will be negative, leading to an outward initial acceleration and contact force. However, the patch is also subject to centripetal acceleration, $-r\omega_z^2$, after contact. Therefore a worst-case estimate of the inertial forces that the adhesive patch has to resist is:

$$\mathbf{f_c} = m_p \cdot \begin{bmatrix} -r\omega_z^2 \\ (\omega_z r - v_y)/\delta t \\ 0 \end{bmatrix} \tag{2}$$

where m_p is the mass of the contact patch that attaches to the target. This inertial force needs to be compared to adhesive constraints:

1) $f_{cx}/A_{patch} \leq \sigma_{max}$, the strength of the adhesive in the normal (initially x) direction, where A_{patch} is the contact patch area. We note that σ_{max} depends on the applied shear load [39] and the patch will tend to peel at whichever edge first exceeds this limit.
2) $f_{cy}/A_{patch} \leq \tau_{max}$, the maximum shear stress. This constraint limits the initial tension on the tether attached to the adhesive patch.
3) The maximum *speed of adhesion*, as noted in [40]—that is, the maximum speed at which the gecko-inspired adhesive can engage a surface in dynamic loading scenarios. This limit applies to the time interval, δt, over which the adhesive shear stress ramps from zero to the maximum value, τ_{max}.

In the limit, for large objects, if $r\omega \gg |\mathbf{v}_0|$, the adhesive requirement is dominated by the centripetal acceleration and the speed of adhesion. Once the tether starts to wrap around the rotating target, the capstan effect quickly dominates so that the maximum tether tension is given by:

$$f_t = (\tau_{max} A_{patch}) e^{\mu\theta} \tag{3}$$

where μ is the coefficient of friction between the tether and the target. In reality, the maximum tether tension is likely dictated by the AV's control authority. Tether length is assumed to be much greater than the target object diameter, allowing AVs with weak thrusters to apply a small amount of tension over an extended period, gradually reducing or eliminating the rotation. This control scheme—though beyond the scope of this paper—may involve a combination of tether tension, AV thrust, and contacting the object with one or two booms, which can now apply contact forces without concern that the object will be lost or pushed away.

IV. Experiments

We recognize that many questions must be addressed before the Gecko Lasso concept can become a reality. Among them, one important question is under what conditions the adhesive will attach reliably to rotating objects. We present initial experiments to address this question, focusing on the need to attach to a spinning surface without assistance from gravity.

Satisfying adhesive constraint 3) in section III-A above is critical to allowing adhesive engagement. In this initial experiment, we investigate the allowable speed of adhesion when attaching to cylindrical target objects. An experimental testing apparatus was designed to engage the tethered adhesive with a controllably rotating target. The target rotates about a single axis to simplify apparatus design and reduce the number of extraneous variables affecting adhesive performance results.

A. Fabrication and Apparatus Design

The testing apparatus consists of a rotating arm with a fixed torque to gently bring a tethered adhesive patch into contact with a rotating target. The target was mounted vertically, with its axis of rotation horizontal, as shown in fig. 4. The adhesive engagement point was chosen to be along the bottom of the cylinder, providing a "worst-case" scenario for engagement. Target and lasso engagement orientation were chosen to ensure that gravity opposes surface contact and therefore does not promote patch conformation or adhesion. A rigid arm was used instead of a translational boom to hold the value of v_x constant during testing. A foam suspension was affixed to the end of the arm to support the adhesive.

The prototype was fabricated using a 2.5×2.5 cm thin-film adhesive cast onto a flexible 0.025 mm Kapton backing layer. The Kapton layer was extended beyond the end of the adhesive to allow connection to a nylon tether without wrinkling. The tether length was kept short for these experiments to prevent it fully wrapping around the cylinder and creasing the adhesive patch. In practice, the tether would be much

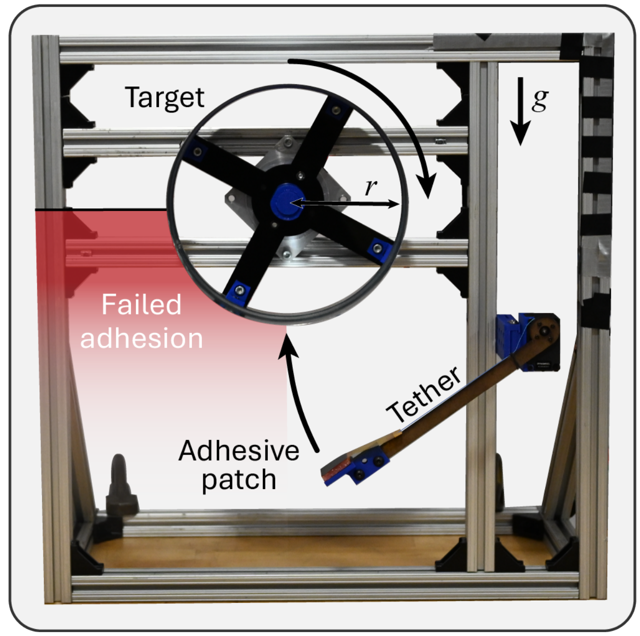

Fig. 4. Adhesion testing apparatus: a metal cylinder of radius r rotates at an angular velocity ω and is approached by an adhesive patch held temporarily by an arm with a soft suspension. The arm contacts at an inward radial velocity v_x. Red "Failed adhesion" region shows the range of trajectories taken when the adhesive failed to attach.

longer, but a short tether is easier to handle when focusing only on initial attachment. A small amount of tension was applied to the tether using a rubber band 3 cm from its end; friction between the tether and arm/rubber band is assumed to be constant across all experiments.

The target is a moderately smooth zinc-plated steel cylinder (a piece of sheet metal ducting) with radii of $0.075\,\mathrm{m}$, $0.01\,\mathrm{m}$ and $0.0125\,\mathrm{m}$. The target velocity is controlled by a DC servomotor, with angular velocities up to $33\ \mathrm{rad\,s^{-1}}$.

B. Procedure

During each test, the fixed-torque arm gently rotated the adhesive patch into the spinning target. The adhesive trajectory following initial attachment was recorded at $240\ \mathrm{frames\,s^{-1}}$. Binary "adhered" and "not adhered" test results were recorded, where "adhered" samples remained engaged on the target for more than a quarter revolution. (After 1/4 revolution, the adhesive is unlikely to detach.) When "not adhered," samples detached from the target in the "failed adhesion" region highlighted in fig. 4. Each target was tested at nine different angular velocities, with six trials conducted at each level. A single adhesive sample was used throughout testing to eliminate sample-to-sample variation and to demonstrate the ability for a patch to survive many attachment cycles. No noticeable patch degradation was observed throughout the experiments.

V. Results

Tests showed that attachment and wrapping were usually successful ($\geq$ 90% success rate) on $0.075\,\mathrm{m}$, $0.01\,\mathrm{m}$ and

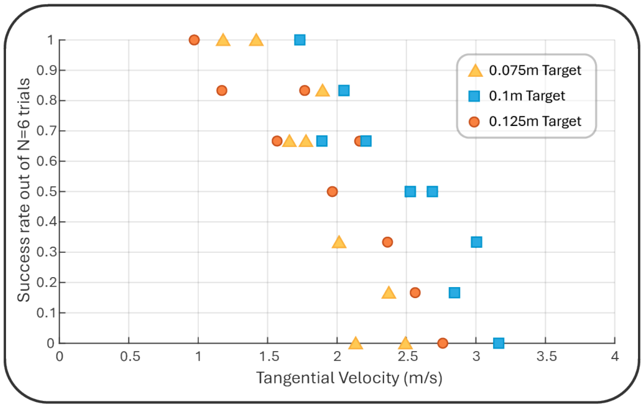

Fig. 5. Successful attachment probability decreases with increasing tangential velocity for different radii of curvature.

$0.0125\,\mathrm{m}$ metal cylinders whenever the tangential surface speed was below $1.3\ \mathrm{m\,s^{-1}}$. The main results are summarized in fig. 5.

It remains too early to say whether constraints 1) or 3) in section III-A were the dominating factor contributing to adhesive failure. However, we note that as the Gecko Lasso concept is applied to successively larger orbital objects, the centripetal acceleration will be smaller for a given tangential surface speed. In the regime of this experiment, the centripetal acceleration is already several times that of Earth's gravity, and thus may have a larger effect on initial engagement here than when attaching to much larger objects in orbit. Other factors, such as whether the adhesive patch conformed uniformly, or whether minor differences in target roughness or geometry affected the results, remain to be investigated more carefully.

The results of these experiments are encouraging and motivate additional analyses and experiments concerning full 6 degree of freedom dynamics and tether control, durability in space, etc. It is also important to note that the graspable speeds found in this experiment are not meant to establish an upper bound for the speed of adhesion. Rather they build confidence in the ability to attach to spinning objects without any assistance from gravity. As noted in the next section, the speeds tested here are comparable to those anticipated for objects in orbit.

VI. Discussion and Future Work

We have presented a gecko-inspired concept of attaching to and potentially de-tumbling and capturing rotating orbital objects using a flexible tether. The approach involves using a small, light, and flexible patch of anisotropic gecko-inspired adhesive attached to a long tether and deployed using an extendable arm or boom. The very low mass of the adhesive patch allows it to make initial contact with a relatively high mismatch in velocity between the patch and the object surface. In preliminary benchtop tests, attachment was reliable for surface speeds of up to $1.3\ \mathrm{m\,s^{-1}}$. Higher velocity mismatch is likely possible with a more precise design. To the authors' knowledge, these relative tangential speeds are already higher than reported for previous applications of gecko-inspired adhesives—for example, Estrada, *et. al* report tangential velocities up to $\approx 0.2\ \mathrm{m\,s^{-1}}$.

To put the tested rotation speeds in perspective, a few example targets for which rotation has been measured include the Ariane5 R/B (28904) and the JAXA H-II A R/B (43682). These two pieces of target debris boast tangential velocities of $\approx 0.459\ \mathrm{m\,s^{-1}}$ and $\approx 0.034\ \mathrm{m\,s^{-1}}$ respectively [41]. Even large rocket body debris that measures $\approx 4-5\ \mathrm{m}$ in diameter would require an angular velocity of $> 0.5\ \mathrm{rad\,s^{-1}}$ to fail consistently using the results of our attachment experiments as a guide.

A number of future extensions are required to refine the concept and increase its level of technology readiness. Adhesive limits should be investigated to enable *reliable* attachment within the constraints of the Gecko Lasso use case: (i) Though initial testing reported in this work is promising, maximum speed of adhesion remains to be thoroughly investigated. (ii) Though nominally smooth, many target surfaces may have degraded due to exposure in orbit. Since gecko-inspired adhesion decreases with increased surface roughness, maximum roughness for reliable contact should be investigated and compared with that of potential target objects. (iii) Since Gecko Lasso poses a rendezvous scenario in which the adhesive must be applied tangent to the target surface and orthogonal to its primary axis of rotation, the adhesive must be able to tolerate a certain amount of misalignment. As such, nominal allowable misalignment limits should be characterized. We note that although all of these factors affect adhesive performance, reduced adhesion due to target speed, roughness, or misalignment can be accommodated through overall device and adhesive design choices.

Target control after successful contact with the tumbling object should be investigated. This includes, but is not limited to: (i) free-floating planar experiments and simulations to explore post-contact dynamics. These should include scaled-up experiments that more closely match dimensions of target debris. (ii) Extension to a 3-dimensional case through simulation or gravity-offloaded experiments. Targets may be tumbling about multiple axes of rotation and adhesive patch placement may not be able to align with the target's center of mass [21]; these scenarios should be explored when designing control schema.

Environmental concerns regarding the adhesive, backing film, and tether must also be addressed. As noted in section II-B, a number of these have been addressed in other work for gecko-inspired adhesive films, albeit at low velocities.

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