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Supplementary Materials for

A robotic device using gecko-inspired adhesives can grasp and manipulate large objects in microgravity

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Other Supplementary Material for this manuscript includes the following:
available at robotics.sciencemag.org/cgi/content/full/2/7/eaan4545/DC1

Movie S1 (mp4 format). The force and moment limit surface of a four-unit flat gripper in the *x*-*z* (shear-normal) plane.
Movie S2 (mp4 format). The force and moment limit surface of a four-unit flat gripper in the *y*-*z* (shear-normal) plane.
Movie S3 (mp4 format). The force and moment limit surface of a four-unit flat gripper in the *x*-*y* (shear) plane.
Movie S4 (mp4 format). The force and moment limit surface of a two-unit curved gripper in the *x*-*z* (shear-normal) plane.
Movie S5 (mp4 format). The force and moment limit surface of a two-unit curved gripper in the *y*-*z* (shear-normal) plane.
Movie S6 (mp4 format). The force and moment limit surface of a two-unit curved gripper in the *x*-*y* shear plane.
Movie S7 (mp4 format). Demonstration of the 2D and 3D floating tests of the grippers.

MATERIALS

Silicone elastomers have been used to manufacture dry adhesives for space applications due to their stability in extreme environments. Space-grade controlled low volatility silicones, including NuSil CV-1142P and CV2-2289, have a wide elastic temperature range and meet NASA specifications for outgassing. The stiffening temperature is -115ºC, and the physical properties do not change until 450ºC (for short periods) and 180ºC (one year). Tests have been performed to -60ºC (*8*), limited by the force sensor range and chamber costs. Resistance to radiation was examined in (*27*), where the radiation level was orders of magnitude stronger than in Earth orbit. The other major challenge for materials in earth orbit is atomic oxygen. Here again, space-qualified silicone elastomers are superior to most polymers. A gradual accumulation of stiffer, silica material forms on exposed surfaces over the course of several years (*48*). It is unclear whether this layer will reduce adhesion, flake off under use, or generate contamination concerns. However, a working lifetime of at least one and probably several years can be expected based on previous observations of silicone elastomers in space (MISSE, MIR, Hubble). Life is longer if the adhesives are kept oriented in anti-RAM directions (away from the direction of motion).

METHODS

List of Symbols

W_{ext}	External wrench vector
F_{unit}	Gripper unit actual adhesion
F_{limit}	Gripper unit adhesion limit
F_1	Adhesive force of the left film
F_2	Adhesive force of the right film
N_1	Contact force of the left in-rigger
N_2	Contact force of the right in-rigger
θ_{max}	Maximum rotational deflection
$M_{plateau}$	Moment plateau of an SMA wrist
M_{limit}	Moment limit of a gripper
E_{max}	Maximum absorbed energy
t_{peak}	Time corresponding to peak deflection
I	Moment of inertia of a gripper system
$F_{loading}$	The loading force of an SMA wire
$F_{unloading}$	The unloading force of an SMA wire
r	Ratio of the unloading and loading forces
t_{settle}	Settling time of a wrist
b	Rotational damping of the a spring-damper wrist
ω_n	Natural frequency of a spring-damper wrist

Combined force and moment modeling

In general, we can compute the combined force and moment capabilities of both flat and curved grippers in six-dimensional wrench space. First, we assume a unity generalized force and moment wrench vector W_{ext} in any given direction. Then, we calculate the corresponding adhesion F_{unit} at each gripper unit level based on the gripper geometry and the point where the moment is evaluated. This is possible because of the load-sharing system. The limit for each unit is as shown in Fig. 4A and B. We then scale W_{ext} by F_{limit} / F_{unit} until any of the units would fail. Repeating this process for each W_{ext} will produce the limit surface.

For 2D loading plane projections, it is convenient to take advantage of symmetry and use a specialized procedure. Specifically, for flat grippers first we compute the gripper unit level adhesion caused by an external force and then can add a moment until the adhesion limit is reached. For curved grippers we use the individual film adhesion limit in a similar process. As noted in the main paper there are three cases.

Case (1): For the flat gripper X-Z (shear-normal) plane loading, the pure force limit curves (the X-Z slice of the 3D force limit surface in Fig. 4A) are convex. Thus moments can only be added to forces that are within the limit curve. The effect of a moment depends on the choice of coordinate system, taken here as embedded on the object surface at the centroid of the gripping area. For general loading we consider also the reaction forces produced by outriggers.

For the flat gripper Y-Z (shear-normal) plane loading, the modeling is the same as above except that the Y-Z plane slice of the 3D force limit surface (Fig. 4A) is used. For curved gripper Y-Z plane loading, the Z axis normal force is determined by the film X_{ad} adhesion (*38*), and the Y axis shear force is the same as the film Y_{ad} adhesion. Thus, with the limit curve shown in Fig. 4B the combined force and moment capability can also be calculated. As with flat gripper X-Z plane loading, the limit surface is symmetric.

Case (2): For both the flat and curved gripper X-Y (shear) planes, moments about the Z axis (i.e. “twisting”) are supported by the hard stops in the pulley differential. In the prototype we placed the hard stops such that all units' hard stops are hit almost simultaneously when an external ``twisting" moment is applied, yielding the most Z-axis moment capability. The adhesion capability is analyzed for this geometry. Note that for the gripper in Fig. 2 all units are arranged in a single row along the Y axis, therefore Z-axis moments are balanced only by X forces.

Case (3): For the curved gripper with an external load in the X-Z plane, there are four possible reaction forces: compressive forces N_1 and N_2 on the two in-riggers and shear forces F_1 and F_2 on the left and right film pieces. The adhesive film and tendon have finite stiffness, and by design the in-rigger contact points have much greater stiffness. Thus, without a pretension in the gripper, if both film pieces have adhesion, then due to film stretch the two in-riggers cannot simultaneously contact the surface. If only one film piece is in tension, then the two in-riggers must simultaneously contact the surface for a stable grasp, yielding three equations and three unknowns. Therefore, inside the X-Z plane without pretension, there should always be up to three active reaction forces. At transition loading conditions, depending on which film reaches its adhesion limit first, there can be 6 different scenarios when calculating the combined force and moment limits. The scenarios are listed as follows:

- F_1 reaching limit, F_2 being zero, N_1 and N_2 being nonzero,
- F_1 being zero, F_2 reaching limit, N_1 and N_2 being nonzero,
- F_1 reaching limit, F_2 not at limit yet, N_1 being nonzero, N_2 being zero,
- F_1 not at limit yet, F_2 reaching limit, N_1 being nonzero, N_2 being zero,
- F_1 reaching limit, F_2 not at limit yet, N_1 being zero, N_2 being nonzero,
- F_1 not at limit yet, F_2 reaching limit, N_1 being zero, N_2 being nonzero.

With the same external force, the reaction force scenarios can vary based on the total moment. With an X axis pure shear force and no moment, it is possible to have both in-riggers compressing the object the same time, which is very different from the flat gripper. With any external X and Z force, we traverse all the six scenarios to calculate the Y moment capability in both Y+ and Y- directions. There are at most two scenarios that are valid given an X-Z plane pure force, and there is always at most one scenario that is valid for a combination of forces and moments. Thus, we sweep the X-Z plane force space and calculate the moment capability accordingly. If there is no valid solution for a given force, then this external load is out of the limit. For generality and simplicity we analyze all the forces and moments with respect to a coordinate system centered at the intersection of the tangent lines of the film pieces.

Note that for any given external force, a positive moment and a negative moment contribute to different compressive force directions due to the curvature and thus may lead to different reaction force scenarios. Therefore, the reaction force and moment capability in the X-Z plane is not symmetric. Furthermore, in some situations an external force can make one film piece have larger adhesion than the other. If a moment is in the direction that counteracts this adhesion difference, more force can be applied with, than without this moment. If the gripper is pretensioned before loading, it is possible that all four reaction forces are active. The pretensioning gives one more equation, and thus all the forces can be solved.

Nonlinear wrist analysis

For simulation, the simplified loading curve of the SMA wire is used. Note that the unloading force is approximately 0.3 times the loading force. Therefore, for each loading cycle, the SMA wire absorbs all the energy during loading and releases 30% of the previous energy absorbed back to the system. To make the most use of such a wrist, we set the force plateau just under the gripper's adhesion limit in this loading direction. For a rotational wrist, with a maximum deflection of θ_{max}, the absolute total amount of energy absorbed is:

$$E_{max} = M_{plateau}\theta_{max} \tag{1}$$

where $M_{plateau}$ is the moment plateau of the wrist, which is set approximately the same as the gripper load limit M_{limit}. The time that the wrist reaches its peak deflection is:

$$t_{peak} = \sqrt{\frac{2E_{max} I}{M_{plateau}}} \tag{2}$$

where I is the moment of inertia in the loading direction of the gripper. The total settling of the system can be determined based on a 1% oscillation amplitude criterion. This is approximately the same as 1% residual energy, which makes the calculation easier. For each cycle the wrist absorbs 30% of the energy left from the previous cycle. The settling time can then be calculated based on an integer number of cycles n as follows:

$$r = \frac{F_{unloading}}{F_{loading}} \tag{3}$$

$$\sum_{i=1}^{n} (1-r)^i = 1 - 0.01 \tag{4}$$

$$t_{settle} = \sum_{i=1}^{n} \sqrt{\frac{2E_{max}(1-r)^{i-1} I}{M_{plateau}}} (1+r) \tag{5}$$

where r is the ratio between the SMA's unloading force plateau and loading force plateau.

For a spring-damper based wrist, the maximum moment occurs either at the initial impact with the damping moment being the highest and the spring moment being zero or at the largest deflection with damping moment being zero or the spring moment being the largest. These two moment peaks must not exceed the adhesion limit. Anywhere in the middle of the process the moment is less than the peak moment. Therefore, comparing to the best SMA wrist that holds the gripper's moment limit during the first stretching cycle, any spring-damper system can absorb less energy than the best SMA system given the same deflection range (stroke). Similarly, with the same amount of energy, a spring-damper takes more time and deflects more to fully absorb that energy than the best SMA system. Specifically, with the same amount of energy an under-damped system has slightly less peak deflection than a critically-damped or over-damped system, whereas a critically-damped system has much less settling time than the other two. It can be proved that for a critically damped system the largest force/moment occurs at impact. With the adhesion constraint and a fixed amount of energy to absorb, the time at the maximum deflection of the best critically damped system is $1/\omega_n$, where ω_n is the natural frequency of the system. Thus, the maximum deflection can be calculated as follows:

$$b\sqrt{\frac{2E_{max}}{I}} = M_{limit} \tag{6}$$

$$\begin{aligned} \theta_{max} &= \sqrt{\frac{2E_{max}}{I}} \frac{1}{\omega_n} e^{-1} \\ &= \frac{4E_{max}}{eM_{limit}} \end{aligned} \tag{7}$$

where b is the damping coefficient. The settling time of the critically damped system can be calculated as follows:

$$
\begin{aligned}
t_{settle} &= \frac{7.64}{\omega_n} \\
&= \frac{15.28\sqrt{2E_{max}I}}{M_{limit}}
\end{aligned}
\tag{8}
$$

CAPTIONS

Movie S1. The force and moment limit surface of a four-unit flat gripper in the *x-z* (shear-normal) plane. The dots are experimental data; the surface is the combined force and moment limit surface; and the red line is the pure force limit in the X-Z plane. The limit surface is symmetric in all 4 quadrants.

Movie S2. The force and moment limit surface of a four-unit flat gripper in the *y-z* (shear-normal) plane. The dots are experimental data; the surface is the combined force and moment limit surface; and the red line is the pure force limit in the Y-Z plane. The limit surface is symmetric in all 4 quadrants.

Movie S3. The force and moment limit surface of a four-unit flat gripper in the *x-y* (shear) plane. The dots are experimental data; the surface is the combined force and moment limit surface; and the red line is the pure force limit in the X-Y plane. The limit surface is symmetric in all 8 quadrants.

Movie S4. The force and moment limit surface of a two-unit curved gripper in the *x-z* (shear-normal) plane. The dots are experimental data; the surface is the combined force and moment limit surface; and the red line is the pure force limit in the X-Z plane. The limit surface is symmetric about the origin.

Movie S5. The force and moment limit surface of a two-unit curved gripper in the y-z (shear-normal) plane. The dots are experimental data; the surface is the combined force and moment limit surface; and the red line is the pure force limit in the Y-Z plane. The limit surface is symmetric in all 4 quadrants.

Movie S6. The force and moment limit surface of a two-unit curved gripper in the *x-y* shear plane. The dots are experimental data; the surface is the combined force and moment limit surface; and the red line is the pure force limit in the X-Y plane. The limit surface is symmetric in all 8 quadrants.

Movie S7. Demonstration of the 2D and 3D floating tests of the grippers.