Scaling Controllable Adhesives to Grapple Floating Objects in Space

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***Abstract*— As the number of rocket bodies and other debris in Earth's orbit increases, the need to capture and remove this space junk becomes essential to protect new satellites. A low cost solution may include gecko-inspired directional adhesives, which require almost no compressive preload to generate adhesion and are therefore suitable for surface grasping in space where objects are free floating. Current individual adhesive units with a pair of opposed pads achieve a limit of 13N normal to the surface. Instead of using a single large unit to generate high levels of adhesion, using multiple small gripper units is desirable to prevent single-point failures and to conform to higher curvatures. For this strategy to succeed, it is essential to distribute the overall force evenly, to minimize the overall preload normal to the surface, and to prevent local failures from propagating over the array. We present two load sharing mechanisms. The first uses nearly-constant force springs in parallel. The second uses a tendon and pulleys in series. Both allow a 4-unit gripper to maintain the same adhesive stress as a single unit. A normal adhesive load to compressive preload ratio of 100:1 is demonstrated. Zero gravity experiments and air bearing floor experiments demonstrate the gripper's functionality in a simulated space environment. Design considerations are discussed for further scaling, with the trade-offs among load sharing, suitability for different surfaces, and failure sensitivity.**

I. Introduction

According to NASA orbital debris reports [1,2], there are currently more than 13,000 rocket bodies and pieces of debris in Earth orbit, and the number has increased by more than 20% in the past 5 years. Collisions between satellites and debris have caused many millions of dollars of losses. Grappling and removing orbital debris would keep active satellites safe and make room for new satellites. As most debris objects are no longer controlled, disposing of this debris will require grappling non-cooperative targets, something that has yet to be accomplished in space.

Traditional grasping methods usually require either opposed fingers or arms which compress two faces on the object to generate adequate friction force, or a gripper which wraps around an object to hold it. A summary of the extensive literature is provided in [3]. However, many debris objects do not have accessible features to grasp or would require very large grippers to create the necessary wrapping. Some previous examples of grappling systems relied on cooperative targets with pre-designed grapple features, such as the Canadarm on the International Space Station [4] and the Orbital Express

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Fig. 1: An autonomous multi-unit gripper anchoring to a carbon fiber panel in zero gravity.

docking system [5,6]. On the other hand, surface grasping with van der Waals and electrostatic adhesion does not have these requirements. Electrostatic adhesives [7,8] have better ON/OFF controllability but less strong adhesive stress than gecko-inspired fibrillar mushroom-tip adhesives [9,10]. A soft inflatable gripper with fibrillar adhesives [11] shows improved ON/OFF controllability but the air inflation is not compatible with space applications. Unlike either of the above adhesive solutions, controllable gecko-inspired adhesive grippers provide stong adhesive stress with little attachment and detachment effort [12], making them suitable for use on solar panels and the sides of spacecraft, fuel tanks, and other similarly smooth objects. Such materials and grippers have also been tested for thousands of loading cycles [13], in a simulated space environment [14]–[16], and with robotic arm teleoperation [17]. The contribution of this paper is on extending these results to larger loads and applied moments with efficient scaling method, to increasing the robustness of the solutions to localized failures (e.g due to dirt or surface defects), and to the ease of autonomous attachment and detachment for space applications where gravity is negligible.

The current surface gripper unit uses a pair of $6.5\,cm^2$ adhesive pads to generate $\approx 13\,N$ of normal force on flat, clean glass sheets. A much higher load capability is desired to manipulate large debris objects of $100\,kg$ or more. Thus, a larger area of adhesive is required. To make use of a large adhesive area, load-sharing is required. Other research has used different load-sharing strategies in different scenarios. One solution uses a fluid-filled sac with pressure plates and tendons [18]; however this is not suitable for use in space. Another solution uses inextensible fabrics with reversible elastometic adhesives for large scale shear-load sharing [19]. A more recent solution for human-scale climbing uses an array of tiles with parallel constant force springs [20]. Each of these solutions assumes that the applied load will be in a single direction, and predominantly in shear. For space applications, the load may be mostly in the normal direction and may include bending moments with respect to the surface. To meet these requirements we present two load-sharing strategies for large scale normal adhesion ($\approx 50\,\mathrm{N}$) that are compatible with space applications: a parallel constant force spring system and a differential pulley system. A preload-sharing strategy is also introduced to minimize the total normal compressive force.

Design requirements for scaling up to a multi-unit gripper for space applications are presented in Section II. Next, corresponding solutions of each design requirement are explained in Section III. Specifications and load-sharing results of a four-unit gripper are given in Section IV, as well as test results from zero gravity and air bearing floor experiments. A comparison of load-sharing strategies and an improved constant force spring design are presented in Section V. The paper concludes with a discussion of ongoing work to scale to even larger sizes, adhere to curved surfaces, and combine van der Waals force adhesion with electrostatic attraction for enhanced "pull in" when conforming to surfaces.

II. Design Requirements

A. Adhesion Capability

A gripper must have a strong and robust adhesive capability to grip and manipulate large objects in space. Instead of using two large tiles with opposed adhesives, an array of gripper units with small tiles is used, helping conform to potential curvature, easing manufacturing tolerances, and improving the resilience of a grip to failure of a single tile. Rigidly attaching units together results in unevenly distributed adhesion forces among units due to manufacturing tolerances. The unit that reaches its adhesion limit first will fail, but other units will still be well below their adhesion limits, so that the total load is far below the maximum potential load. In contrast, a perfect load-sharing strategy enables every gripper unit to reach the individual adhesion limit simultaneously, maximizing the potential load. The load sharing strategy should also be robust: the failure of a few units due to surface defects or adhesive damage should not severely compromise the overall performance.

B. Moment Capability

A gripper must sustain applied moments to manipulate an object after it is grasped. This requirement entails producing a mixture of normal adhesive and compressive forces to achieve a moment. Increasing the moment capability requires either large forces or long moment arms to increase $\vec{r} \times \vec{f}$. While the compressive force can easily be made large, adhesion is limited. On the other hand, large moment arms can result in a bulky gripper that is difficult to handle.

C. Compressive Attachment Force

In space, objects are easily accelerated and pushed away. Therefore a space gripper must exert as little initial compressive force as possible when attaching to a surface. As discussed in Section III, a single-unit gripper requires less than $0.1\,N$ normal preload to engage with a flat, clean surface and can generate more than $13\,N$ normal adhesion force. It is important to maintain this favorable ratio as the design is scaled to multiple units. Preload should ensure that all pads engage the surface without pushing the object away.

D. Other Space Application Related Requirements

Once the multi-unit gripper grasps a target surface, the gripper should lock and prevent itself from detaching even under zero load. During manipulation, the grip should be stiff, without "play" or slack, so that continuous relocalization of the object is unnecessary. Slack could result in manipulation delays and, if the object accelerates within a loose grasp, it could produce an impulse as the end of travel is reached. In addition, the gripper should be able to detach easily on command, effectively "turning off" the adhesion when it is time to release the object.

III. Design Solution

A. Gripper Unit Design

A gripper unit consists of two $6.5cm^2$ tiles with gecko-inspired directional (controllable) microwedge adhesive [21] oriented in opposite directions, as shown in Fig. 2. These adhesives have been tested in full vaccum under -60° Celsius with over 30,000 ON/OFF cycles. In the neutral state, pre-tension tendons hold the adhesive tiles parallel to one another along the long axis of the unit, allowing passive alignment to the surface. When the gripper is engaged by loading the central tendon, the two tiles are loaded at an equal angle (usually about 10°) to turn the adhesives ON. Shear forces on the two adhesive tiles cancel out, leaving a net normal adhesion force. After the load is removed from the central tendon, the adhesive returns to the OFF state. Tensioning the release tendons introduces moments to the adhesive tiles to peel them from the surface.

B. Multi-unit Gripper Design

The multi-unit gripper has two levels: the gripper unit level and the load-sharing level (Fig. 3). All the gripper units are assembled to be as co-planar as possible to minimize the effort needed to align tiles with a surface. However, manufacturing errors are hard to eliminate, and thus compliance is needed to accommodate displacement differences among units. Very soft linear compression springs, which are much smaller in size than the tiles, are attached to the center of each tile making a compressible pivot so that each tile has compliance and can accommodate a gentle surface curvature. The other ends of these springs are free. This prevents tiles from being loaded through tension in the springs. Each gripper unit has a tube to guide the central tendon and reduce any motion in shear directions.

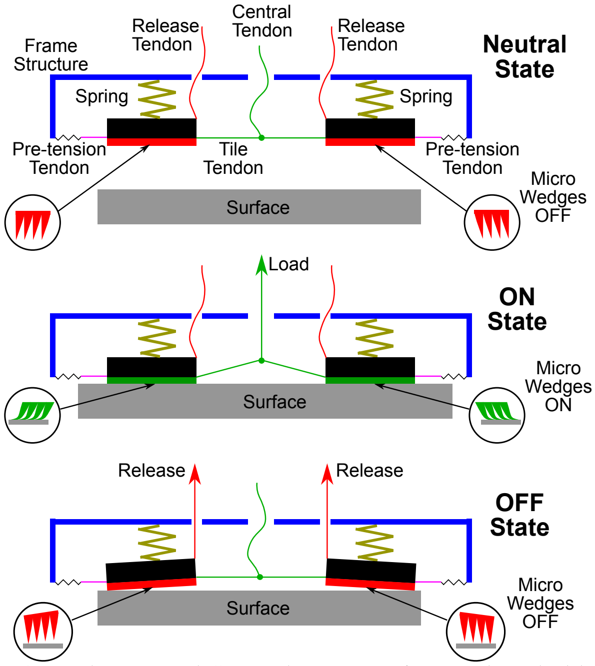

Fig. 2: In the Neutral State, the pre-tension tendons hold the adhesive tiles flat for ease of engagement. In the ON State, the adhesive tiles are loaded at a fixed angle. In the OFF State, the tiles are peeled from the surface with the release tendons.

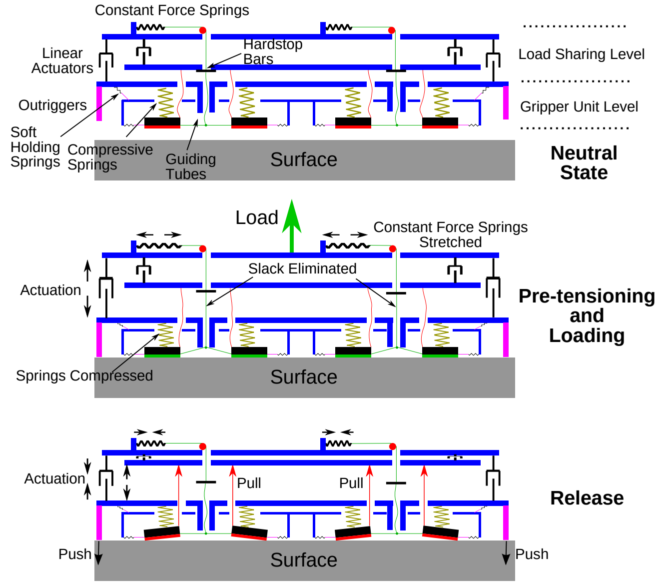

Fig. 3: Three working states of a parallel nearly-constant force spring mechanism for load sharing.

Next we consider two different load sharing mechanisms: the parallel nearly-constant force spring mechanism and the differential pulley mechanism.

1) Parallel Nearly-Constant Force Spring Mechanism: Fig. 3 illustrates the parallel nearly-constant force spring mechanism; an image of the actual device is shown in Fig. 5 (left). Each gripper unit is attached to the lower frame with soft springs, as described in the previous section. Each central tendon is routed through a hole in the upper frame and attached to a nearly-constant force spring. A hard-stop bar is located in the middle of the tendon to limit its motion. The force plateau of the nearly-constant force springs is tuned to be below the adhesion limit on a target surface. In addition, there are several outriggers, shown in magenta in Fig. 3, at the periphery of the lower frame. The outriggers help to align the entire assembly with a surface.

For release, there are release tendons (shown in red) attached to the middle frame. There are also two linear actuators. There is a longer linear actuator between the top frame and bottom frame for locking and pre-tensioning, and a shorter linear actuator between the top and middle frame for releasing. In the neutral state the hard-stop bars prevent the nearly-constant force springs from loading any gripper units, so that the central tendons are slightly slack in this state. Each release tendon is also slack.

Once in contact with the surface, the longer linear actuator increases the distance between the top and bottom frames to eliminate any slack in each central tendon while moving the outriggers down to the surface. As the load applied to the gripper increases, the adhesion force in each gripper unit grows unevenly until it reaches the force plateau of the nearly-constant force spring. Thus each gripper independently experiences an increasing force that ultimately plateaus at a limit which is set by the springs. Once all gripper units have reached the plateau, the total force remains nearly unchanged as the springs continue to stretch. Because the force plateau is slightly below the adhesion limit for each gripper unit, the gripper remains safely attached. In this way, the adhesion capability of the multi-unit gripper is maximized. If a single unit fails prematurely, the force in the remaining gripper units can continue to increase until the plateau is reached.

To release, the longer actuator releases tension in the central tendons, then the shorter linear actuator decreases the distance between the top and middle frames until the release tendons become taut. In this state, the releasing force is an internal force generated by pushing against the surface with outriggers while pulling the release tendons. Thus all the units detach from the surface without applying a net force to the target object.

2) Differential Pulley Mechanism: The differential pulley mechanism is shown in Fig. 4. Instead of being attached to independent nearly-constant force springs, all the central tendons are connected with a pulley mechanism. There is a linear spring in parallel with a short loop of the tendon (shown at top of Fig. 4) to pre-tension it and prevent it from falling off the pulleys. Once the tension exceeds a threshold, this spring straightens and compliance is eliminated. The rest of the notation as well as the working states are the same as for the nearly-constant force spring mechanism. Ideally (i.e., without friction) the tension in the pulley rope is the same everywhere, making the tension in all the central tendons equal. Thus all the gripper units are guaranteed to share the load evenly. This design is a type of differential mechanism, and is different from the nearly-constant force spring mechanism, where the units share the load unevenly at first before approaching the same upper limit. In this design, should some units fail before others due to surface non-idealities or pulley friction, the hard-stop bars prevent too much slack from the failed units from being transmitted to the remaining working units, which would cause the outriggers to lift from the surface. Fig. 4 is a functional illustration of the mechanism; the actual device is shown in Fig. 5 (right).

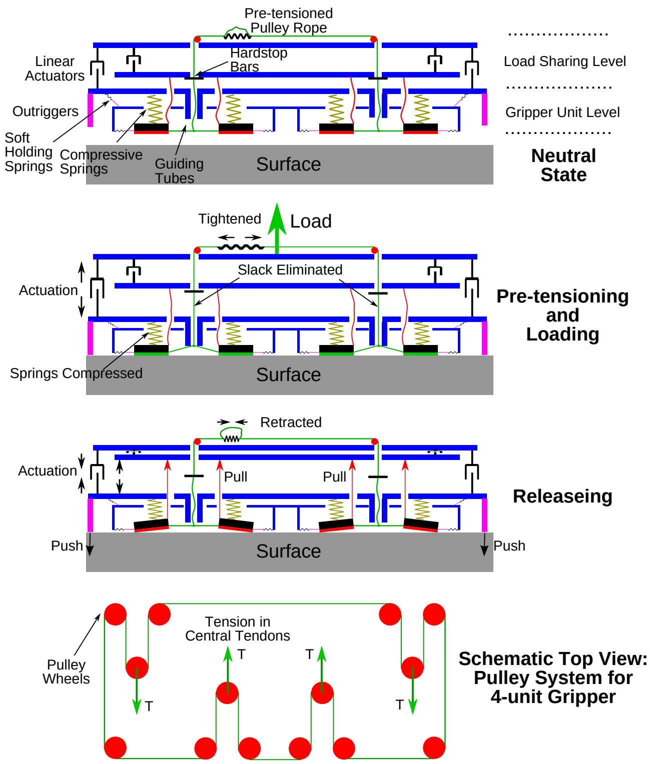

Fig. 4: The upper three figures illustrate the working states of a pulley mechanism. Only two units are shown for simplicity. The bottom figure is a flattened schematic view of the pulley mechanism for a 4-unit gripper.

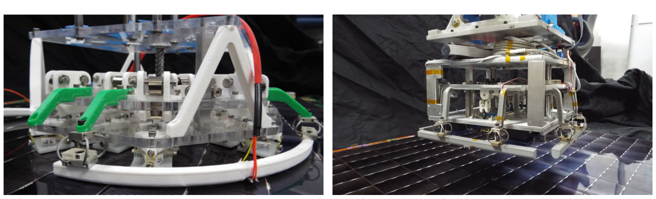
Fig. 5: *Left:* A prototype 4-unit gripper with a parallel nearly-constant force spring mechanism. *Right:* A prototype 4-unit gripper with a differential pulley mechanism.

3) Applying Moment: Outriggers help to increase the moment capability of the multi-unit gripper by allowing all gripper units to remain in adhesion while the outrigger experiences compression (shown in Fig. 6).

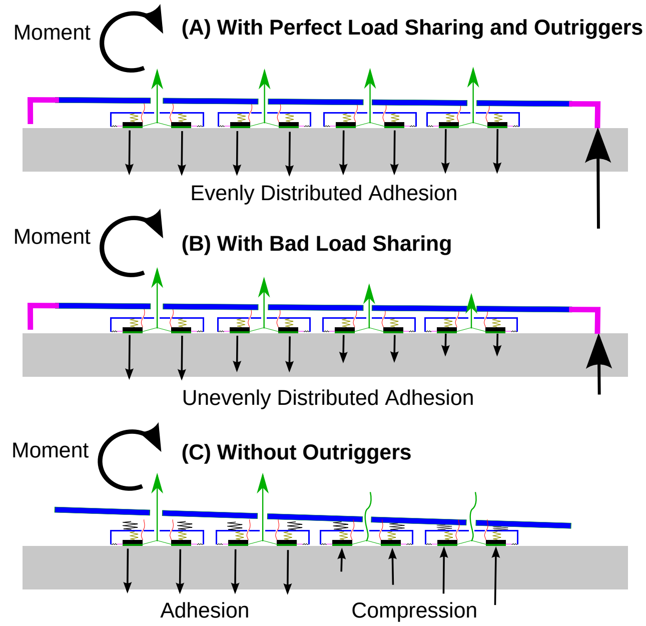

Fig. 6: Load-sharing and outriggers help to maximize moment capability. Without load-sharing, the adhesive forces are unequal, reducing the maximum possible moment. Without outriggers only some of the gripper units are in adhesion, the rest in compression.

C. Integration

An aluminum gripper with four gripper units was built for high fidelity experiments. Previously, the gecko-inspired directional adhesives were molded from a space-qualified silicone rubber. The silicone was previously tested in a thermal-vacuum chamber and on over 30 spacecraft surfaces [14]. In the aluminum gripper, the gripping units are actuated using a lead screw mechanism driven by a DC motor and worm gear to prevent back-driving under load. The grapple event happens in less than 0.5 seconds. However, this is often longer than the communication time-delay to spacecraft, so autonomous grappling was implemented using four contact switches on the outriggers and a single axis force sensor to detect overall preload. The gripper is commanded to actuate when at least 3 of the 4 contact sensors are depressed (indicating flush alignment) and the force sensor registers a minimum preload.

A two-axis gimbal mechanism is used to accommodate misalignment of the gripper to the target. This system has a range of +/- 35 degrees and uses light torsion springs to return to a neutral state when not engaged. Two stages of damping are used to improve the ability to manipulate objects after grappling. Very light damping is provided by torsional dampers in the +10 to -10 degree range to allow easy alignment and stiffer linear dashpots are used to provide much higher damping beyond 10 degrees for manipulating large objects. In the future, damping could be provided and continuously tuned by a multi-jointed robotic arm with compliance control [22]. Locking brakes were also prototyped but led to high impulse forces and frequent loss of grip during manipulation tasks. The gimbal can be manipulated by an operator (as in the zero-g tests described below) or mounted to a fixture (as in the air bearing floor tests described below).

IV. Results

A. Load Distribution

Two 4-unit grippers, one with a nearly-constant force spring mechanism and one with a pulley mechanism, were built to test load-sharing performance against a 4-unit rigid control case. Super-elastic Nitinol Shape Memory Alloys (SMAs) and metal tape constant force springs were used as constant force springs. V-grooved ball bearings and PowerPro Spectra fishing lines were used for pulley wheels and tendons. Linear actuators were made of either servo driven spools or motor driven lead screws on different devices. Force sensing experiments used Phidgets micro load cells. The sensor sampling rate was 10 Hz as the force loading rate of individual load cell is slow (approximately $2\,N/s$).

The results of normal adhesion load-sharing are shown in Fig. 7. The results show the normal adhesion force of the individual units versus the total normal adhesion force for 5 trials. Due to different experimental setups, all the force profiles are normalized to a percentage of corresponding maximum loads. For the 4-unit gripper with rigidly attached tendons (Fig. 7(A)) each unit has a significantly different load throughout the cycle. The force profiles for different trials are not repeatable because the angle of the structure is slightly different for each trial so that some tendons are loaded more than others in different trials. For the 4-unit gripper with the nearly-constant force spring mechanism (Fig. 7(B)), the 4 units first share load unevenly, similar to the "rigidly attached" gripper, and then share the load evenly after all the springs have reached the plateau force. The unit that reaches the force plateau first holds its force and "waits" for other units to reach this region. The key point of this load-sharing strategy is to keep every gripper unit safely adhered while initially disregarding the detailed force distribution before the force plateau. Different trials have different details of the force profiles before the force plateau, but they all converge to the same region. For the 4-unit gripper with the pulley mechanism (Fig. 7(C)), the 4 units always share the load evenly. The slight deviations among the force profiles of individual units is a result of pulley wheel friction. Detailed load/preload-sharing performance of the 4-unit gripper with the pulley mechanism is shown in Table I. The external force needed to release the 4-unit grippers are approximately $0.0065\,N$, and the adhesive force to releasing force ratio is approximately 7,700/1.

B. Testing in Zero-G

Testing was performed aboard NASA's C-9B aircraft, the *Weightless Wonder*, to achieve two objectives. First, a simple hand-held gripper using a single pair of large $58cm^2$ pads mounted on a foam backing and linear rail was demonstrated grappling rigid targets by a floating operator. This mimics situations when a small inertia object grapples a large inertia object, for instance an astronaut gripping the International

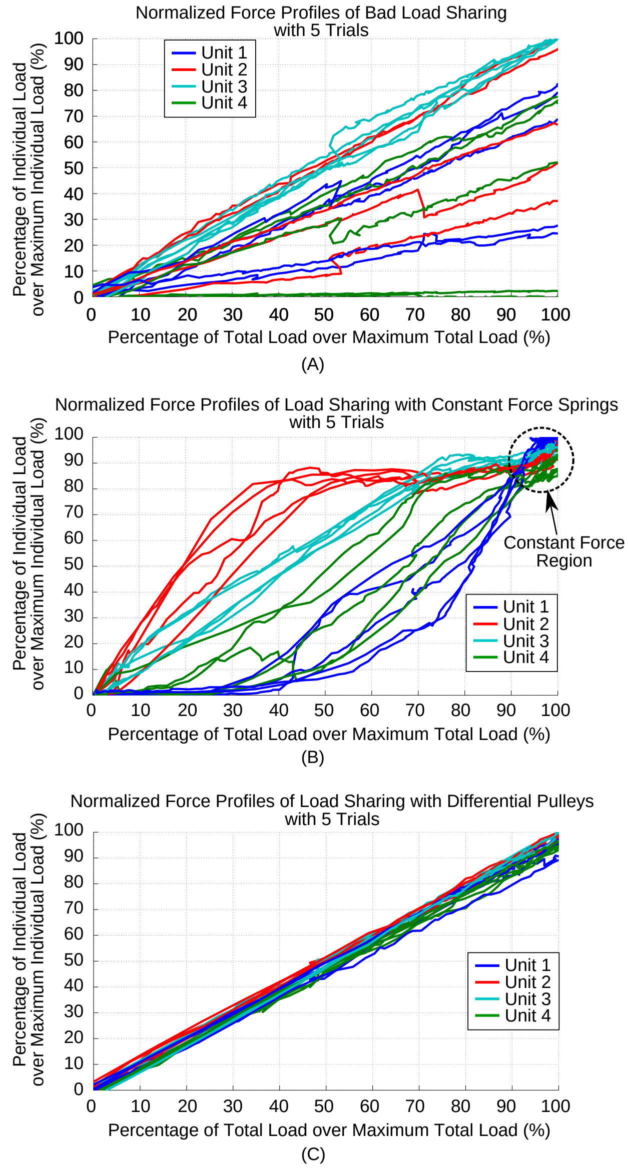

Fig. 7: load-sharing results for 5 trials with 3 different grippers: *top*, with rigidly attached tendons, *middle*, with the parallel nearly-constant force spring mechanism, and *bottom*, with the differential pulley mechanism. The force profiles are data points connected according to time line. For the test rigidly attached tendons, the zig-zag patterns at some parts of the curves indicate sudden load shiftings from one gripper unit to another, which is caused by the unstretchability of the tendons and angle change of the body plates.

Specifications	Single-unit Gripper	Multi-unit Gripper	Scaling Performance (Real Over Expected)
Compressive Preload	0.1N	0.5N	80%
Normal Adhesive Load	13N	50N	96%
Ratio of Normal load to preload	130	100	77%
Shear Adhesive Load	45N	170N	94%
Moment about Normal Axis	N/A	4.73Nm	97%
Moment about the other 2 Axes	N/A	5.7Nm	94%

TABLE I: Functional specifications of a single gripper unit and a multi-unit gripper with pulley mechanism.

Space Station, or a CubeSat docking to a large satellite. Six-axis force/torque data was logged for these trials on anodized aluminum, mylar blanket, carbon fiber sheet, and an ISS server rack panel on loan from the Astronaut Crew Office. The gripper performed above expectations, supporting up to $85\,N$ of pull off force. Figure 1 shows one such test.

The second objective was to grapple non-cooperative floating targets using a floating tool. This test simulates capturing a piece of orbital debris or docking two satellites of similar inertias. Demonstrations of grapple, manipulation, and release were accomplished with the autonomous gripper on $10\,kg$ and $100\,kg$ targets using aluminum, carbon fiber, and mylar surfaces. The supplemental video shows some of these tests. Detaching easily in space is crucial to a safe mission as it prevents large transfers of momentum to either the object or target that could overwhelm the attitude control system of the spacecraft. It is, in part, for their inability to release easily that pressure sensitive adhesives like tapes and non-directional fibrillar adhesives are a poor match for applications in space.

C. *Testing on an Air-Bearing Floor*

System level dynamic testing was performed at JPL's Formation Control Testbed, also known as the Robodome, using two $370\,kg$ floating robotic spacecraft. In the facility, both robots float on the flat floor providing frictionless relative motion and allowing grapple testing under more representative mass and inertia contact dynamics. The $370\,kg$ robot can be easily accelerated across the flat floor with a tiny push using only one finger. Successful autonomous grappling of a non-cooperative target was demonstrated using compressed air thrusters aboard one of the robots to chase and grapple the second robot as it drifted away with a solar panel exposed (Fig. 8). Upon contact, the gripper autonomously actuated, at which point the propulsive direction of the thruster system was reversed and the simulated debris was dragged to a desired location, stopped, and then released with a near-zero force detachment. Exact velocity measurements were made using a Vicon motion capture system. This end-to-end demonstration is a step towards a fully autonomous spacecraft that could hunt for and remove the most dangerous orbital debris objects. The supplemental video shows one of these demonstrations.

D. *Testing inside the International Space Station Mock-Up*

Testing was performed in coordination with the Crew Training Office at NASA's Johnson Space Center inside the ISS Mock Up. A handheld gripper could be used in space as a reconfigurable handhold, camera or laptop mount, or to preload acoustic emissions sensors or accelerometers into a surface to detect micrometeorite impacts or perform other non-destructive evaluation tasks. Successful grip was achieved on approximately half of the exposed surfaces. Failures were largely due to high surface roughness or exposed topography like bolt heads, buttons, and rivets.

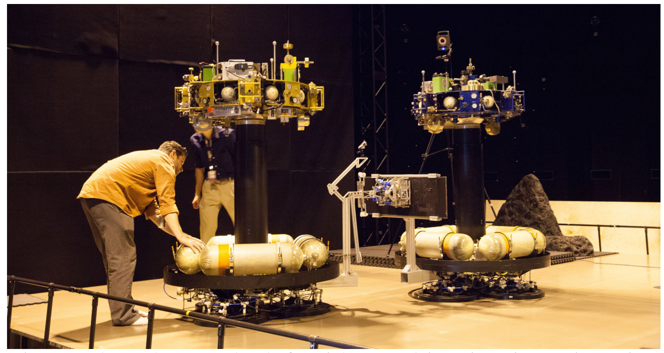

Fig. 8: The robot on the left with a multi-unit gripper is trying to grapple the robot with on the right with a solar panel. The two robots are floating on the floor with air bearings.

V. FINDINGS

The results show that multi-unit grippers with the either parallel nearly-constant force springs or the differential pulley mechanism have much better load sharing than those with rigidly attached tendons. Between these two load-sharing strategies there are some trade-offs, especially in aspects related to space applications. The following sections present several comparisons between the two strategies for scaling and provide guidance for choosing strategies for different situations. Insights from the tests are presented after the comparison.

A. *load-sharing Effectiveness*

To evaluate how effective a load-sharing strategy is, we define effectiveness with a modified coefficient of variation as follows:

$$Effectiveness = (1 - \frac{\sigma_F}{\mu_F}) \times 100\% \quad (1)$$

where σ_F is the standard deviation of the adhesion forces of all units and μ_F is the average adhesion force of all units. The adhesion forces used in the calculation correspond to the forces right before failure. A perfect load-sharing corresponds to an effectiveness of 100%.

For the pulley mechanism, experiments were conducted to test the effectiveness for further scaling up to 14 gripper units with a similar pulley configuration as introduced in Section III. As the number of units increases, the effectiveness decreases due to friction accumulation (shown in Fig. 9). Other pulley configurations may result in less total friction but would fill more volume. On the other hand, for the nearly-constant force spring mechanism, the effectiveness is only determined by the manufacturing errors of different nearly-constant force springs. Theoretically one could purchase an arbitrarily large number of springs and only use the ones with arbitrarily similar performance, or specify a tight tolerance on these parts. For practical reasons, we present the effectiveness of different number of units as no better than that of the hand-built 4-unit gripper with nearly-constant force springs, selecting from around 20 springs. As shown in the comparison, the parallel nearly-constant force spring mechanism has better load-sharing effectiveness than the pulley mechanism when the number of units is greater than 4. Thus for scaling up to more than 4 units, the nearly-constant force spring mechanism is a better choice in terms of effectiveness.

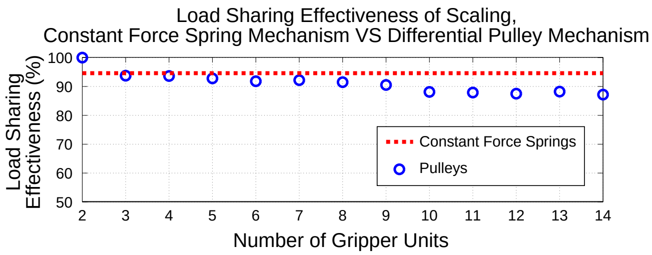

Fig. 9: load-sharing effectiveness comparison between nearly-constant force springs and pulleys.

B. Suitability for Different Surfaces

Sometimes it is not known on what surfaces the multi-unit gripper will be used, or it may target multiple pieces of debris with different surfaces. For the nearly-constant force spring mechanism, the force plateau should be tuned below the adhesion limit of a unit, which may vary by surface type. If the force plateau is larger than the adhesion limit, the gripper with this mechanism would perform similarly to the one with rigidly attached tendons. Thus the constant force spring mechanism, once manufactured, only works on specific surfaces. Some constant force springs like SMAs are also sensitive to temperature change, thus not robust to changing environments. However, the pulley mechanism ideally has even load-sharing at any total load, which is independent of surface adhesion limit and environment. Therefore, the pulley mechanism is more surface and environment insensitive than the nearly-constant force spring mechanism.

There is an alternative nearly-constant force spring mechanism, designed for robustness on different surfaces. Instead of using a single nearly-constant force spring for each unit, we connect a set of springs with different force plateaus in series for every unit. Each spring has a limited stretchable length. As the total load increases, the nearly-constant force spring with the smallest force plateau stretches first and then bottoms out, and then the spring with the spring with the next smallest force plateau stretches and bottoms out, and so on. The test results for a prototype of this design are shown in Fig. 10. The figure shows that the spring that reaches the force plateau first keeps stretching and "waits" for other springs to reach the force plateau. There are 3 force plateaus, and the force profiles of the 4 units diverge and converge 3 times. The different force plateaus could be tuned to be below the adhesion limit on different surfaces. An estimation of surface adhesion limit is needed.

C. Failure Sensitivity

Due to non-idealities of a surface, e.g. large contaminants or flaws, the adhesion limits of some units might be less than others and cause premature failures. In the parallel nearly-constant force spring mechanism each unit is independent,

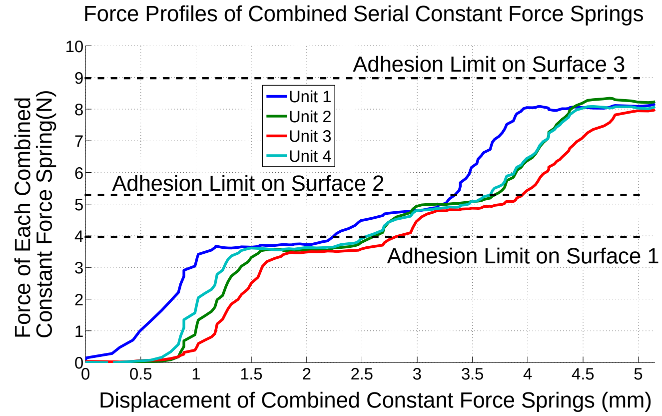

Fig. 10: Results from the nearly-constant force spring mechanism modified for loading on a variety of surfaces. The 3 plateaus correspond to the adhesion limits on 3 different surfaces.

thus failure of some units does not affect the others. In the differential pulley mechanism, hardstop bars prevent slack from being transmitted to other units. However, due to the imperfect rigidity of the system, the hardstop bars are sometimes a slight distance away from the stop position when the total load is large. Thus, as the number of failed units increases there is additional slack transmitted to the remaining working units. This could cause manipulation delays and even failure of the whole gripper. Robustness to single unit failures is an advantage of the nearly-constant force spring mechanism.

D. Space Application Related Findings

Understanding the scaling properties of the directional adhesives was critical to building large-scale grippers that were reliable and could support large loads. Combined with prior experiments, the results presented here of tests in a zero-g aircraft, on a large air-bearing floor, and inside the ISS mock up are paving the way for a demonstration of directional adhesives in space within the decade. Once mature, this cross-cutting technology could be used for orbital debris mitigation, in-space assembly of large structures, satellite servicing, spacecraft inspection, autonomous rendezvous and docking, and as an astronaut aid.

VI. CONCLUSIONS

We present scaling strategies to help maximize the attainable adhesive loads and minimize the compression preload for a multi-unit gripper in grasping applications for space. Laboratory experiments show that the scaled normal adhesive loading capability is 96% of the ideal value and that the scaled normal compressive preload is 80% of the ideal value. Design insights for further scaling indicate that serial pulley mechanisms are generally less effective in load sharing than parallel nearly-constant force spring mechanisms when the number of gripper units is high, but are more suitable to different surfaces because the loads in individual units are nearly equivalent regardless of total load. Analysis also shows that parallel mechanisms are more robust to failures and slack in the system than serial mechanisms. Future work includes implementing a 10-unit gripper on a robotic arm for fully autonomous surface grasping and manipulation. Curved surface grasping and scaling will also be explored. Electrostatic adhesion can also be added to the current grippers [23] to enhance adhesion on rougher surfaces.

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