Gas-Lubricated Vibration-Based Adhesion for Robotics

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Controllable adhesion has the capability to enable mobile robots to move freely across vertical and inverted surfaces for applications such as inspection, exploration, and cleaning. Previous methods for generating controllable adhesion have relied on fluidic adhesion through suction forces, electromagnetic adhesion through magnetic or electrical interactions, or dry fibrillar structures. Herein, a new method for achieving controllable adhesion by vibrating a flexible plate near a surface, which generates a strong and controllable attraction force, is presented. This adhesion mechanism has the unique property of providing strong adhesion normal to a surface, but very low resistance to motion parallel to the surface, making it attractive for mobile robots. Adhesive capabilities of vibrationbased adhesion (VBA) to characterize adhesive force dependence on vibration frequency and surface size are studied. Spatial pressure measurements within the adhesive zone, in combination with visualization of surface vibration modes. demonstrate that adhesion is localized to the center of the disk and decreases radially. A mobile robot to highlight the capabilities and robustness of VBA for payload transport, climbing to inversion transitions, and adhesion control is developed. Overall, a novel physical mechanism for robot-surface adhesion that is robust, controllable, and enables rapid low-friction locomotion is presented herein.

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1. Introduction

Controllable adhesion, the ability to selectively attach or detach from a surface, is an essential capability for many engineered systems, such as material processing equipment, wall-climbing robots, and pick-and-place machinery. Robots capable of controllable adhesion have applications for inspection and repair, surveillance, and exploration of environments unsuitable for humans.^[1,2] A variety of controllable adhesion techniques have been proposed to enable these use cases, including methods relying on pneumatic, electromagnetic, and dry fibrillar adhesive forces between a robot and a surface. While existing techniques are often effective, they usually require relatively heavy and energyconsuming components and/or intrinsically link high normal and shear adhesion.

In this work, we develop an adhesion mechanism that relies on the fluidmediated adhesive force between an oscillatory plate and a surface. This lightweight, low-power mechanism provides high

normal—but low-shear—adhesion, making it uniquely suitable for robotic applications including mobile robots and some manipulation tasks.

Previous approaches have used active pneumatic adhesion (i.e., suction)^[3,4] or strong electromagnets or permanent magnets^[5] to demonstrate high adhesive stresses to enable wall climbing for relatively heavy systems (e.g., $\sigma_{max} = 20.1$ kPa for an individual suction unit weighing 0.8 kg^[6]). However, these approaches are, in general, limited to nonporous and ferromagnetic surfaces, respectively. In addition to surface restrictions, these systems usually require additional bulky hardware (i.e., traditional pumps and magnets). Despite these disadvantages, some pneumatic and electromagnetic approaches do have the advantage that they do not require direct contact with surfaces for adhesion. Thus, adhesion can be maintained while the manipulator or mobile robot smoothly slides across the adhering surface. This non- or light-contact mode of adhesion may be advantageous for mobile inspection robots that have to move easily across surfaces.

Active pneumatic adhesion is advantageous in that pumps are commercially available and are relatively straightforward to control and integrate into a physical system. However, at small scales, these advantages are lost as the manufacturing of micro-electromechanical system micropumps^[7] requires specialized high-precision equipment. Some studies have investigated



small-scale pneumatic fluidic adhesion,^[8] but controllable adhesion has not been demonstrated.

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While electromagnetic adhesion requires compatible ferromagnetic surfaces, electrostatic adhesion, or electroadhesion, is applicable to nonferrous surfaces. Electroadhesion generates an adhesive force via applying a high voltage (hundreds to thousands of volts) to a patterned conductor.^[9–12] The high voltage generates a localized electric field that-when placed in close proximity to a substrate-causes an adhesive force. Electroadhesion provides large forces on a variety of surfaces and consumes very low power. However, the performance of electroadhesives decreases on rough substrates and is susceptible to the accumulation of dirt or dust on the adhesion interface.^[13] although recent work has demonstrated an electrostatic cleaning method that shows improved performance on contaminated surfaces.^[14] Furthermore, the high voltages required for electroadhesion lead to challenges with portability, safety, and miniaturization.

The power and weight requirements for pneumatic and electromagnetic adhesion have made it challenging to design systems at smaller scales (i.e., from mm to cm scale) that use these strategies. In the past two decades, a variety of adhesion methods inspired by biological adhesive systems such as gecko toes (dry fibrillar adhesives^[15]) and insect feet (capillary and tunable soft interfacial adhesion,^[16-18]) have been proposed to address these size and weight limitations. Dry fribrillar adhesives use patterned arrays of soft microstructures to induce Van der Waals interactions between the substrate and the microstructure.^[19-23] This approach provides high strength-to-weight performance and requires no energy to maintain adhesion but is limited to low force angles.^[24] In addition, the adhesive strength of these approaches degrades on dirty surfaces.^[25,26] Capillary adhesion occurs between surfaces through an intermediate wetting layer. Adjusting the wetting layer volume and viscosity can control adhesion force and ultimately enable or disable adhesion to the surface. However, capillary adhesion requires a supply of fluid, surfaces that have appropriate wetting properties (e.g., hydrophilic for a water-wetting layer),^[27] and are subject to degradation and fouling from chemical and particulate contaminants on the surface.^[28]

Hybrid systems that use both dry fibrillar adhesives and electroadhesives have been shown to improve overall adhesion, especially on rough surfaces.^[29] However, many of the previously mentioned limitations remain. Biomimetic suction for marine environments has expanded the capabilities of controllable adhesive suction disks by allowing them to adhere to a wider variety of substrate types and roughnesses.^[30] Similarly, capillary forces in combination with fibrillar structures can enhance adhesion on dry, hydrophilic surfaces.^[31] Critically, fibrillar-based adhesives require contact with the surface and often achieve adhesion in combination with high friction. Thus, these adhesives do not enable smooth and easy sliding of manipulators or robots across the adhering surface.

These tradeoffs between contact and noncontact adhesives highlight a demand for low-weight, noncontact, and low-friction mobile adhesive mechanisms that can be used in fluids such as air and water. One such potential for fluid-mediated noncontact adhesion is through the suction force between two smooth, rigid plates, immersed in a fluid. When two surfaces immersed in an incompressible fluid are separated, there is an adhesive force, often called Stefan adhesion, generated between the two surfaces. This force results from the motion of fluid as it fills the gap. However, because Stefan adhesion is generally modeled to scale with the relative normal motion between the surfaces, it cannot provide a steady-state adhesive force. In this work, we demonstrate that a persistent adhesive force can, however, be generated between a flexible disk and a stationary surface by oscillating the disk in air. To the best of our knowledge, this effect has not been used previously to achieve controllable adhesion.

We explore a novel gas-lubricated controllable adhesion technique that uses vibration to generate high adhesive forces with commercially available hardware (Figure 1A). We conduct static and quasistatic loading tests to investigate the maximum supportable load of a flexible disk excited by an eccentric rotating mass (ERM) motor (Figure 1B,C). We test a range of disk radii and motor driving frequencies to assess the effect on the maximum adhesive strength. We measure the radial pressure gradient in the fluid film for a representative adhesive strength test and compare it with the micron-scale displacement over time of the vibrating disk for several cases of static loads. Finally, we present a two-wheeled direct-drive robotic instantiation to highlight the design principles and capabilities of this adhesion method. By developing a low-weight active suction strategy that is simple to manufacture, we aim to expand the toolbox of controllable adhesion and illuminate opportunities to build new hybrid adhesion systems.

2. Design Principles

Analytical models for lubrication theory problems show a heavy dependence on the thickness of the lubricating fluid film. For the well-known case of Stefan adhesion,^[32] the resulting force varies with $1/h^3$. In general, most analytical models prescribe the thickness of the fluid film and this is done in practice by controlling the flowrate or the pressure of the air in the case of an aerostatic bearing or by controlling the gap via some external mechanism.^[33] When we brought a vibrating plate in close proximity to a smooth surface, the system spontaneously adhered and a steady-state fluid film emerged. Thus, if the geometric and control parameters were chosen correctly, the physical system would inherently maintain a low-pressure region of ambient air and a gas film with an average thickness on the scale of hundreds of microns (Figure 6).

The mobile robot consists of two primary subsystems: 1) a flexible disk with a vibration source that excites vibrations normal to the surface to generate adhesion and 2) a drive system that provides stable contact between traction wheels and a surface to enable locomotion. In the following subsections, we describe in detail the design and evaluation of each of these subsystems.

2.1. Adhesive Subsystem

2.1.1. Vibration Source

To generate vibration of the adhesive disk, we used vibration motors (commonly used to generate haptic feedback). In the



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Figure 1. A flexible disk is capable of spontaneously generating an adhesive force if excited by a vibration motor when in close proximity to a surface. We used this mechanism to design a mobile robot capable of controllable and low-friction adhesion to surfaces at any orientation. A) A two-wheel direct-drive robot uses a 6.9 cm radius vibrating disk and two drive wheels to traverse a curved, overhanging surface. B) The mobile robot is capable of supporting over 3.8 N when excited with a small ERM vibration motor. See Video 3, Supporting Information, for a short clip of an untethered direct-drive system acquiring and carrying a 0.38 kg load (a full soda can). C) In air, a vibrating flexible disk, placed in close proximity to a substrate, will generate negative pressure in the thin gas film. The negative-pressure region generates a substantial adhesive force that provides high normal adhesion with low resistance to lateral movement (figure not to scale, the gas film is less than 1 mm thick, see Figure 6 for detailed measurements). D) Close-up of an ERM motor showing the eccentric mass that generates a sinusoidally varying vertical force when rotated.

majority of our experiments, we used ERM motors as they provided the ability to control the amplitude of the maximum acceleration by pulse-width modulation (PWM) of the input voltage. The vibration in these motors is generated by rotating a mass; as a result, they provide an oscillatory force that is not confined to a specific axis of motion. Instead, when the rotational axis is parallel to the surface of the vibrating plate, the ERM provides oscillatory forces that vary sinusoidally with time in the orthogonal and transverse directions. Precise frequency control requires some kind of feedback, either by use of an encoder, measurement of back electromotive force (EMF), or by counting commutation spikes. In adhesion experiments, we used a more precise linear resonant actuator (LRA) to generate plate vibration. LRAs provide excitation along a single axis and require an AC signal to drive, meaning that the frequency can be controlled open loop. However, the low vibrating mass of these systems also means that generating large vibration amplitudes requires the system to operate at a resonance frequency. For this reason, we limited the use of LRAs to characterize experiments that required vibration in only a single direction.

2.1.2. Flexible Disk

The vibration source is mounted to a flexible disk to generate vibrational motion near the adhesive surface. There are three main design parameters for a uniform flexible disk: 1) disk material, 2) disk thickness, and 3) disk radius. The first two

parameters have a significant effect on the bending stiffness of the disk and thus will influence the vertical deflection of the disk under vibration. Thicker disks require higher oscillatory forces from the motor to generate plate bending and deflection. Altering the disk radius will change the disk area and, consequently, the resistance to lateral movement and normal motion will change. Changing the radius will also change the stiffness of the disk.

To gain insight into how the geometric properties of the disk influence the bending and ultimately the vibration properties, we use the equation for symmetric bending of a clamped disk to estimate the effect of the earlier parameters on the stiffness of the disk.^[34] The stiffness for a circular plate, subject to symmetric bending, of Young's modulus, *E*, Poisson's ratio ν , thickness, *t*, and radius *R* is given by

$$k = \frac{16\pi E t^3}{12(1-\nu^2)R^2} \tag{1}$$

This equation provides initial insight into the scaling of bending deflection of circular plates under vibration. Minor changes to the thickness of the disk can be used to tune the stiffness of this disk to match the vibration amplitude range of our motor.

For the experiments described in the following sections, we used the earlier equation to choose values for *R* that ensure that each disk had equivalent stiffness across tests. We used flexible plastic shim stock material of prescribed thickness, *t*, and used the derived relationship $k_1 = \frac{t_1^3}{R_1^2} = \frac{t_2^3}{R_2^2} = k_2$ to estimate values for

the radius which will give an equivalent stiffness for fixed thicknesses of flexible shim stock material. For shim stock thicknesses of $t = [101.6, 127, 190, 254, 318] \mu m$, we calculated the following values of R = [1.75, 2.45, 4.5, 6.93, 9.68] cm.

2.2. Drive Subsystem

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We seek to use vibration-based adhesion for mobile locomotion on vertical and inverted surfaces. The normal interaction force between the vibrating plate and surface is adhesive; thus, a drive system is required to generate traction to move laterally along the surface. We measured the transverse friction due to shear in the thin fluid layer between the disk and an acrylic surface (**Figure 2**). For a polyester disk of radius 4.5 cm, we measured a maximum transverse force of 10 mN. This low friction force is consistent with the fact that gas bearings are often used to reduce sliding friction in precision machinery. For disks with a larger radius, we could expect this value to scale with R^2 (disk area), but at small disk sizes, the mass of the whole system (50–60 g) is an order of magnitude larger than the shear force in the fluid film.

To drive up a wall or across a ceiling using wheeled locomotion, the wheels must be able to generate sufficient traction to overcome any losses due to viscous fluid drag (surface friction under the disk), wheel hub friction, and the weight of the system itself (in the case of vertical climbing). Our measurements of surface friction illustrate that vibration-based adhesion generates low friction, making it suitable for smooth locomotion across vertical and inverted surfaces. To aid motor selection, we developed a simple static model of the limiting vertical and inverted locomotion cases to determine the necessary torque for the drive motors as well as the necessary normal force at the wheels.

We used a spring element to both isolate the mass of the drive assembly from vibrations and apply preload to wheels. In addition, as the disk itself was flexible, the center of the disk was expected to deflect under load. Thus, the spring was required to apply preload continuously throughout the range of deflection of the disk to properly isolate the mass of the drive assembly. Furthermore, the force of the spring was required to either exceed the weight of only the drive subsystem (for the case of inverted horizontal adhesion) or generate wheel friction that exceeded the total weight of the system as well as the weight of the payload (for the case of vertical climbing).

2.2.1. Inverted Horizontal Case

To evaluate the limits on locomotion on an inverted horizontal surface, we conduct a static force balance. A free-body diagram is included in Supporting Information (Figure 1, Supporting Information). We find

$$\sum F_z = 0 = m_{\text{tot}} a_z = F_{\text{adh}} - F_{\text{n}} - m_{\text{motor}} g$$
$$- m_{\text{chassis}} g - m_{\text{payload}} g$$
$$\sum F_x = 0 = m_{\text{tot}} a_x = F_{\text{f}} - F_{\text{shear}}$$
(2)

where m_{motor} is the mass of the vibration source and flexible disk and m_{chassis} is the mass of the chassis, drive electronics, orthoplanar spring, and the drive motors. F_{f} is the friction between the wheels and the substrate, F_{n} is the normal force between the wheels and the substrate, F_{shear} is the lateral force due to shear flow in the thin gas film, and F_{adh} is the adhesive force exerted between the disk and the surface.

From the force balance in x in Equation (2), we can see that we only require the friction from the wheels to overcome the shear resistance from the fluid layer. As the fluid shear force is very small (see Figure 2), for motion, we need only ensure that the wheels make contact with the surface. The motor choice is then determined by the desired drive dynamics.

Looking now at the force balance in z in Equation (2), we see that a higher normal force on the wheel corresponds to a lower payload capability. Due to the inherent flexibility of the disk, we know that the whole system will deflect several millimeters away from the surface when under load. Thus, we need to adjust both the preload on the drive wheels and the initial deflection of the spring element to ensure that the wheels maintain contact under the full range of possible loads and the corresponding disk deflections.



Figure 2. Experimental results measuring the maximum available tangential and normal force for vibration-based adhesion in comparison with commonly used adhesive mechanisms. In contrast to other approaches, vibration adhesion uniquely provides strong normal adhesion coupled with low resistance to tangential forces. A) Tests were conducted on an inverted acrylic substrate using an LRA motor on a disk with a radius of 2.45 cm. B) Experimentally measured limits are indicated by red stars. Force vectors which pass outside the green area cause the disk to slip laterally or detach from the surface. Representative regions of adhesive capabilities are shown in blue for isotropic frictional adhesion and purple for Coulomb friction.

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2.2.2. Vertical Case

The case of vertical climbing in general is more challenging then adhesion to an inverted surface due to the presence of moments that cause adhesives to peel off a surface.^[35] This can be mitigated by designing a wall-climbing system to keep its mass as close to the surface as possible. For the purpose of this analysis, we omit the moment balance. If we just consider the static force balance (Figure 1, Supporting Information) we find

$$\sum F_x = 0 = m_{\text{tot}} a_x = F_{\text{adh}} - F_{\text{n}}$$

$$\sum F_z = 0 = m_{\text{tot}} a_z = F_{\text{f}} - F_{\text{shear}} - m_{\text{motor}} g$$

$$- m_{\text{chassis}} g - m_{\text{payload}} g$$
(3)

From the force balance in x in Equation (3), we see that the requirements on motor torque and wheel friction become much stricter than that in the horizontal case. The driving friction from the wheels now must overcome the mass of the entire assembly. This case requires a much higher normal force on the wheels than the previous case. Conversely, looking at the force balance in z in Equation (3), we now see that the adhesion force only needs to resist the normal force of the drive wheels.

Based on this analysis, there is a clear tradeoff between designing for vertical climbing and designing for locomotion on inverted horizontal surfaces. During vertical climbing, the system requires sufficient preload on the drive wheels to generate enough friction to overcome the mass of the system and some negligible shear force. However, in the inverted horizontal case, any preload beyond that required to overcome the very low shear force will decrease that maximum payload. Thus, the design of the internal spring element will determine the range of surface orientations (vertical, inverted horizontal, etc.) that the system will be capable of traversing and the corresponding maximum payloads for each orientation.

3. Results

To investigate the concept of gas-lubricated vibration-based adhesion for robotics, we built two experimental systems: 1) a stationary system, comprising a vibration source and flexible disk, that was used to investigate the adhesive properties of this phenomena (Video 1 and 2, Supporting Information) and 2) a mobile system, additionally incorporating a two-wheeled direct drive mechanism with mechanical isolation, that was used to investigate the design considerations for locomotion (Figure 3). The stationary system consisted of a flexible disk made of lasermachined polyester shim stock bonded to an acrylic adapter plate with threaded holes. The vibration source, an ERM motor mounted to a custom printed circuit board (PCB), was then rigidly connected to the acrylic plate via two threaded spacers and lock nuts. Power was supplied to the system via an external power supply unit (PSU). The mobile system used the same elements as the stationary system but additionally attached a 3D-printed chassis containing drive electronics, batteries, a drive train, and a custom laser-machined orthoplanar spring to the custom PCB. Offthe-shelf remote controlled (RC) components allowed for remote



Figure 3. Computer-aided design renderings and exploded views of the two systems that were used for experimental testing. A) The stationary system consisted of an ERM motor that served as a vibration source and an interchangeable laser-machined polyester disk. Power for the vibration motor was provided using an external PSU. B) The mobile system which additionally incorporated a drive subsystem that was mechanically isolated from the disk and the vibration source. An onboard battery and circuit provided power and remote control functionality.

operation of the robot. We used the stationary system to measure the adhesive forces, stress, and toughness as a function of disk radius and vibration frequency. We then used the mobile system to test the ability of the system to maintain adhesion while driving over flat and curved surfaces at various inclinations and while dynamically capturing a payload.

3.1. Stationary Adhesion Experiments

3.1.1. Measurement of Adhesion versus Displacement

To measure the normal adhesive strength of the vibrating flexible disk, we quasistatically displaced an inextensible nylon string attached to the center of the disk, away from the surface (at a rate of 0.2 mm min⁻¹) until the disk fully detached from the surface. We recorded the maximum adhesion strength while varying two parameters: 1) the driving frequency of the ERM motor and 2) the radius of the disk (**Figure 4**). The adhesive force and displacement were measured with a tensile tester (3367, Instron). As a substrate for all tests, we chose a 25 cm by 25 cm by 0.65 cm acrylic sheet that was mounted to a fixed aluminum frame using vibration damping mounts. We attached the acrylic substrate assembly to the lower fixture of the tensile tester. The nylon string connected the top of the actuation module to the



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Figure 4. Measurement of adhesion versus varying frequency and radius. A) Effect of radius on maximum normal adhesion force. Adhesion force is measured versus normal displacement for five trials across five different disk sizes. From left to right, disk radius is R = [1.75, 2.45, 4.5, 6.93, 9.68] cm and gray circles show relative (not to scale) disk sizes. B–E) Experimental results of (B) max load versus ERM motor frequency (n = 3), (C) max load versus disk radius with a fixed disk stiffness (n = 3), (D) pull-off energy versus disk radius, and (E) max adhesive stress versus radius. Error bars represent standard deviation and n represents the number of trials.

upper fixture of the tensile tester. We used a nylon string as our top fixture to allow for extension without limiting the ability of the disk to vibrate. Any lateral motion of the vibrating disk on the acrylic substrate was prevented using four metal dowels placed around the edge of the disk.

We measured the effect of frequency on adhesion (Figure 4B) using a disk with radius R = 4.5 cm. ERM motors provide large vibration amplitudes but operate over a limited frequency range (\approx 70–300 Hz). We observed that when the disk was excited at frequencies below 150 Hz, no adhesion was achieved at this size of the disk. To drive our physical system continuously above 230 Hz required driving the motor above its maximum rated power and resulting in failure due to overheating. However, at lower frequencies (below 230 Hz), closer to the maximum-rated wattage, we observed no degradation in performance (i.e., the vibration motor operated for 40 min without a noticeable reduction in adhesion). Over the first three frequencies tested (174-190 Hz), the maximum load increased linearly with frequency; beyond this point, the maximum load settled to a constant value of \approx 5 N. We assume that at \approx 200 Hz, the disk had a natural frequency of vibration, and increasing the excitation frequency beyond 200 Hz decreased the amplitude of the dynamic response of the disk.

By comparing the average maximum load for various disk sizes, we can examine the effect of disk radius on adhesion (Figure 4A,C). Disk thicknesses for each radius were chosen to maintain a constant bending stiffness, as predicted by Equation (1).

As the disk radius increased, we observed an increase in the maximum load up to a radius of R = 6.93 cm, after which the maximum load decreased.

An alternative measure of adhesive capability is adhesive toughness or adhesive energy (i.e., the amount of energy required to induce adhesive failure).^[36] Adhesive toughness is a measure of the robustness of adhesion under dynamic or sudden loading. We observe that the pull-off energy, calculated as the area under the force–displacement curve, as a function of radius follows the same qualitative trend as that for maximum load but with a more pronounced optimum at a disk radius R = 6.93 cm.

We normalized the maximum supported load by the area of the disk to get a maximum adhesive stress (Figure 4D). As the radius increased, we observed a monotonic decrease in the average value for maximum adhesive stress. Thus, to support higher loads, it would be more space efficient to use multiple smaller-sized disks then one larger disk (although this configuration would likely be much less energy efficient). In particular, a disk of radius 2.45 cm had approximately an order of magnitude higher adhesive stress than that of a disk of radius 9.69 cm.

For many of the experiments for the stationary system (Figure 4), we observed large variation across trials. We expect that this variation is likely due to the randomness inherent in a vibration-based actuation method. Similar to material testing curves, we expect to see considerable variations between trials due to an element of stochasticity in the phenomena.

3.1.2. Direct Measurement of Suction Pressure and Gap Distance

We measured the pressure gradient in the thin fluid film between the flexible disk and the acrylic substrate with



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piezoresistive silicon pressure sensors (SSCDANN150PAAA3, Honeywell) at five discrete points along the radial direction (placed in ports laser cut into the acrylic substrate at distances in the radial direction of r = 0, 20, 40, 60, 80 mm) (Figure 5A, Video 2, Supporting Information). The same experimental procedure used for the adhesion versus displacement tests was used for these tests. An extension test without the ports for the five sensors verified that the addition of the ports did not significantly affect the load bearing capability of the vibrating disk. We sampled pressure sensor readings at a rate of 500 Hz and measured the vibration frequency of the disk with a high-speed camera (VEO 410 L, Phantom) to be \approx 200 Hz.

From t = 0-175 s, the tensile tester took up slack in the string. During this time, the disk did not experience any appreciable applied load. Despite this, the pressure distribution in the fluid



Figure 5. Representative trial of an adhesive strength test for a disk with R = 9.7 cm. A) Schematic of experimental setup. Five pressure sensors were connected to the underside of ports in an acrylic substrate. A fixed extension rate of 0.2 mm min⁻¹ (applied to the center of the adhesive disk) enforced a quasistatic displacement that increased until adhesive failure occurred. B) Time series data of force and pressure (at all five ports) for a single trial. A moving average filter (2 s sample window) was applied to the pressure readings to average out any intercycle variations. C) Snapshots of interpolated pressure gradients (assuming axisymmetric pressure) taken at three times throughout the test. See supplemental video, Supporting Information, for a continuous visualization of the change in pressure gradient during the test.

film under the disk showed significant negative pressure generation at the center (r = 0 mm), a slight positive pressure at r = 40, and approximately atmospheric pressure at all other sampled locations. At around t = 200 s, the system experienced increased loading, and the magnitude of the pressure in the center increased. At t = 400 s, the magnitude of the pressure in the center decreased and the greater area of the disk experienced negative pressures. We saw this reflected in the sensor placed at r = 20 mm. As the flexible disk was pulled farther from the surface, the gradient became relatively flat from r = 0 mm to r = 20 mm. At t = 630 s, (Figure 5B) the measured force dropped considerably. The maximum force measured before that time $(\approx 5 \text{ N})$ was never recovered. We expect that this was due to a partial detachment event, where a larger area of the disk peeled off the surface. Partial displacement would result in decreased tension in the string and a lower force measurement. The system mass was ≈ 14 g (not including the power supply); thus, the system was able to support a maximum mass of greater than $35 \times$ of its own weight during the test.

As expected from fluids lubrication theory, the maximum negative pressure occurred at the center of the disk and decreased to atmospheric pressure at the edge of the disk.^[37] The localization of the negative pressure, and consequently the load bearing capability, to 4.3% of the total area of the disk (Figure 5C) was unexpected. Only after total extension was increased to a critical point ($\approx t = 630$ s) did the negative pressure gradient became less steep throughout the air film.

Using the signal from the pressure sensors, we created an interpolated field of the pressure acting over the full area of the disk. By integrating this pressure over the disk area, we obtained a value for total force that we compared with the force measured by the tensile tester. Prior to loading, the interpolated pressure signal did not show a net suction force on the disk. Once the disk was loaded, the estimated net force on the disk was the same sign and an order of magnitude as the value measured on the load cell (Table 1, Supporting Information), indicating that the dominant adhesion mechanism was the vacuum pressure generated beneath the disk. It is expected that sampling at more points along the radial direction would result in an estimated net force that is closer to that measured on the load cell.

To further understand how force was generated, we measured the displacement (with respect to the acrylic substrate) of the vibrating disk, subject to a static loading condition. To measure the displacement, we placed fiber optic laser displacement sensors (D21-Q, Philtec, Inc.) through the ports cut into the acrylic substrate and sealed the sensors in place using hot melt adhesive. We measured the steady-state response at seven locations (r = 0, 10, 20, 30, 40, 60, and 80 mm) and tested three loading conditions (F = 50, 300, 600 g suspended from pulleys) for a single-disk design (R = 9.69 cm) (**Figure 6**A).

The steady-state displacement response (Figure 6) showed that at r = 0 mm (the point that the load was applied) the overall displacement increased with greater static load. The measured displacement was a minimum at r = 20 mm for all loading cases. At r = 40 mm, the displacement from the surface was greater, but not as large as the r = 0 mm case. Further out at r = 60 mm and 80 mm, the thickness of the fluid film was significantly greater than that of the innermost portions. These displacement





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Figure 6. Representative data showing steady-state displacement for R = 9.69 cm vibrating disk subjected to a static load. A) Schematic of experimental setup. An optical sensor was used to measure both average displacement and vibration amplitude at discrete points (r = 0, 10, 20, 30, 40, 60, 80 mm) along the radial direction. Steady-state displacement as a function of radius for three static loads: B) 0.50 N, C) 3.00 N, and D) 5.00 N (n = 10). E) The Chladni pattern^[38] for a static loading test ($F_{applied} \approx 5$ N) revealed areas of low-vibration amplitude where sand collected on the disk. There was a large amount of sand at $\approx r = 30$ mm, which correlates with the low average displacement at 30 mm for the 5 N loading case.

responses can be qualitatively visualized using a Chladni pattern,^[38] which uses fine granular media to visualize vibrational nodes (Figure 6E). Sand was poured on the disk during an extension test, conducted at a rate of 10 mm min⁻¹ (Video 6, Supporting Information). At r = 30 mm, we observed a circle of sand, indicating a nodal region. The location of the nodal region qualitatively matches where the previously measured pressure gradient is the steepest. It is possible that the presence of a nodal region limits the flow of air between the inner region of the disk and the outermost region of the disk at higher loads.

3.2. Mobile Robot Experiments

To understand the capabilities and limitations of this adhesion mechanism for robotics, we used the analyses and experiments described earlier to design a mobile robot that used the gaslubricated vibration-based adhesive mechanism. In this design, we added a drive subsystem to the stationary adhesive mechanism described earlier. We mechanically isolated the drive system from the vibration source to maintain the performance of the adhesive system.

3.2.1. Payload Acquisition

To demonstrate the potential of the mobile adhesive robot to be used in a low-cost gantry-less crane system (e.g., for applications such as warehouse or in-home automation), we tested the ability of the mobile system to dynamically acquire a \approx 3.8 N load (a soda can) while adhering to an inverted surface. For this demonstration, the mobile system was equipped with a hook to acquire a payload (Video 3, Supporting Information).

In this experiment, we remotely directed the mobile robotic system to drive along an inverted horizontal surface, hook onto a payload, and drive forward until the payload was no longer supported by an elevated platform. We observed that the dynamic loading caused by dragging the payload off the surface caused the adhesive disk to slide forward and backward along the inverted horizontal surface. This highlights a benefit of using a lubricated adhesion method as the adhesion strength is not significantly affected by transverse loads, such as those imposed by this method of payload acquisition. After the payload was acquired, we were able to resume driving the mobile robotic system along the surface, indicating that the system maintained sufficient preload on the wheels (**Figure 7**).

Previous iterations of the mobile robot design did not have either sufficient preload or static displacement of the orthoplanar spring to accomplish this task. When the wheels lost contact due to the acquisition of the payload, adhesion was not stable and failed shortly after payload acquisition (in \approx 5–10 s). We believe that when the wheels lost contact with the surface, the mass of the chassis was under-constrained and consequently decreased the amplitude of the vibration of the flexible disk, leading to adhesion failure.

3.2.2. Vertical Climbing

Climbing vertical surfaces poses a specific set of challenges for wall-climbing robots. Perhaps most notably, many adhesion strategies tend to fail due to peeling moments that result from off-axis loads. In this experiment, we drove our mobile robotic system up the side of a wooden cabinet (Video 4, Supporting Information). We started the test by placing the mobile system on the vertical surface with the vibration motor turned on. Preload was manually applied to the center of the disk until adhesion was achieved (\approx 5 s). We observed that with sufficient preload applied to the wheels via a spring element, we were able to both maintain adhesion and generate enough friction to overcome the weight of the system and drive up the surface of the cabinet (Figure 8). The inherent stiffness of the disk counteracted any peeling moments that could have caused loss of adhesion (previous wall-climbing robots have accomplished the same thing with a preloaded "tail"^[13]).

3.2.3. Locomotion on Curved Surfaces

In addition to enabling gas-lubricated vibration-based adhesion, we observed that the flexibility of the disk provided robust





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Figure 7. Payload-acquisition experiment. By combining the vibrating adhesive disk with a drive system, we created a mobile robot capable of carrying loads untethered on inverted flat surfaces. A) With the disk vibrating, the robot adhered to an inverted surface. B) Using two drive wheels pressed against the inverted surface with springs, the robot drove toward a ≈ 4 N [≈ 0.4 kg] load. C) With a suspended hook, the robot dynamically acquired the load, carrying on a path determined by the differential drive wheels.

adhesion to nonplanar surfaces with large radii of curvature. To demonstrate this capability with our mobile system, we drove the robot around the interior of a horizontal 0.9 m diameter cylinder (Figure 9, Video 5, Supporting Information). We began the test by placing the mobile robot at the bottom of the cylinder. We then turned the vibration motor on and applied preload manually to the center of the disk until it adhered to the surface. The mobile system drove counterclockwise along the interior of the cylinder in \approx 56 s. Traversing the first half of the cylinder,



Figure 9. Due to the flexible nature of the disk, the mobile robotic system was able to conform to curved surfaces and generate sufficient negative pressures to stay adhered to the inside surface of a horizontal cylinder for a full 360° range of surface orientations.

going from horizontal to vertical to inverted horizontal, took 46 s. Traversing the second half of the cylinder took ≈ 14 s. This makes intuitive sense as it is more difficult for the drive motors to work against gravity than with it. Attempts to rotate the mobile system in place on the curved surface using differential drive steering caused the adhesion to fail. Adhesion failure was likely due to our method of mounting the drive wheels, which lacked independent suspension. As a result, any deviation from a locally straight line on a curved surface caused the preload to increase past the adhesive strength of the disk.

4. Discussion

4.1. Payload for Both Vertical Climbing and Inverted Horizontal Case

The maximum payload the mobile system could support while traversing both inverted and vertical surfaces was limited primarily by the maximum adhesive force that the disk was capable of generating and secondarily by the coefficient of friction between the wheels and the surface material.

$$\overline{F}_{\text{payload}} = \frac{\mu F_{\text{max-adhesion}}}{(1+\mu)} \tag{4}$$



Figure 8. Vertical climbing demonstration on a varnished wooden cabinet. An orthoplanar spring provided sufficient preload on wheels to enable vertical climbing.



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Analytically, we can see that as the magnitude of μ increases, the normalized payload force approaches the maximum adhesion force. However, it is unlikely for μ to be much larger than 1. Assuming a value of approximately unity for μ , we see that the maximum payload force for both inverted horizontal and vertical locomotion is approximately half the maximum adhesion force that the disk is capable of generating. If operation were limited to either vertical climbing or inverted horizontal operation, then the payload could match the maximum adhesive force, with some small offset for system mass.

4.2. Scalability of the Size and Number of Adhesive Disks

A disk of radius 6.93 cm performed the best for both the maximum supported load and maximum pull-off energy; however, the disk with the smallest area had the highest adhesive stress. Depending on the application, it could be advantageous to combine several disk geometries to achieve the desired load capacity and resilience to disturbances.

Due to the relatively low viscosity of air, we expect that as the radius of the adhesive disk decreases, the weight of the vibration source starts to exceed the adhesive strength of the disk. This limitation could be addressed using alternate excitation strategies such as piezoelectrics. As the radius of the disk is increased, there are several factors that could limit the maximum achievable adhesion force. It could be that more viscous losses are introduced as the disk radius increases and so we do in fact get maximum adhesion for a relatively small disk. Alternatively, if we assume that the size of the vibration source would have to be scaled up as the radius of the disk is increased, we might expect the mass of the system to scale with l^3 , whereas the adhesive strength of the disk will scale with l^2 .

4.3. Limited Frequency Sweep and Dynamic Response

Due to our choice of the vibration motor, we were limited in the frequencies we could test. At low voltages, the motor generated low-frequency vibrations but adhesion was not successful. At voltages higher than 5 V, the motors failed due to overheating, as they were operated continuously above their maximum rated power. Future work could use different actuators to investigate a wider range of frequencies and the corresponding dynamic responses of the disk.

4.4. Substrate Roughness

The surfaces used for this work were relatively smooth and lacked significant asperities. Qualitatively, we found that the system adhered only to relatively smooth surfaces (acrylic, medium-density fiberboard, curved, sheet metal, glass) but not rougher surfaces (e.g., stone, bricks, open-cell foam). In our experiments, we measured the maximum fluid layer thickness to be 800 μ m. We found surface roughness to effectively increase the thickness of the fluid layer, consequently limiting the maximum supportable load. We leave a detailed investigation of the effect of surface roughness to future work.

As discussed in this article, gas-lubricated vibration-based adhesion is promising for robotic applications but also faces some fundamental limitations. First, the vibrations required for adhesion are within the range of audible frequencies and as a result, robots that use this mechanism are inherently quite noisy (during testing our system produced a maximum of 88.9 dB(A) of mechanical noise). One solution would be to use these robots in spaces that are not occupied by humans. Another would be to add a noise barrier such as noise insulation foam. Another limitation is that to stay adhered to a surface this system requires energy to be continuously expended, in contrast to controllable adhesion techniques such as dry fibrillar adhesives which passively adhere and require energy expenditure for removal. We additionally found that our system was robust to minor voids in the substrate but failed to maintain adhesion on very porous materials such as open-cell foam. Furthermore, it is unclear whether this adhesion method would work underwater or in a liquid working medium rather than a gas. We expect that both the stiffness of the disk and the amplitude of the vibration force would need to be scaled appropriately to compensate for strong hydrodynamic forces. If these adaptations were successful, they could open up a wide range of additional use cases for underwater adhesion.

5. Conclusion

In this work, we presented and characterized a novel, controllable adhesion method for robotics with high specific normal adhesive stress (i.e., $\sigma_{\rm max}/m_{\rm assembly} = 26.2\,{\rm KPa}\,{\rm Kg}^{-1}$ for our prototype system), comparable with other methods (active suction: $\sigma_{\rm max}/m_{\rm assembly} = 25.1\,{\rm KPa\,Kg^{-1[6]}}$ and hybrid electrostatic and gecko-inspired adhesive: $\sigma_{\rm max}/m_{\rm assembly} = 25.7 \,{\rm KPa} \,{\rm Kg}^{-1[35]}$). In contrast to other controllable adhesion techniques in the literature (e.g., those based on dry fribrillar adhesives, magnetorheological fluids, or electroadhesives), the system was simple to manufacture and leveraged commercially available components to generate high specific normal adhesive stresses with low resistance to shear motion. In our experiments measuring pressure distribution, we observed that the negative pressure produced in a small central region of the vibrating disk balanced the applied load. In the experiments measuring the displacement of the disk, we saw that the delineation of the inner region and outer region approximately matched the location of the minimum fluid film thickness. In addition, we experimentally observed that axisymmetric vibrational patterns are not a necessary condition for adhesion. We hypothesize that the flexibility of the disk allows for the formation of these nodal patterns under a relatively small excitation force and that these nodal regions enable the generation of a small adhesive region at the center of the disk by limiting the flow of air between the inner and outer regions. Further work remains to be done to fully quantify the effects of surface roughness and curvature on adhesion. To allow for this adhesion technique to support larger loads for applications such as warehouse fulfillment or in-home automation, a better understanding of the scalability of this effect with the size and number of adhesive disks is needed.

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Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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adhesions, pneumatic adhesion, robotics, vibrations, wall climbing

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