A Self-Aligning Gripper Using an Electrostatic/Gecko-Like Adhesive

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Abstract—This paper introduces a new robotic gripper for flat surfaces based on a novel electrostatic/gecko-like adhesive. This unique gripping solution overcomes the shortcomings of vacuum grippers for part-handling by eliminating the need for a compressed air system and offering more rapid actuation, thus achieving significant potential cost savings and throughput improvements in manufacturing processes. Results demonstrate the gripper’s performance on a variety of both smooth and rough surfaces, including fabrics, as well as show that the gripper is able to successfully pick up and release glass and carbon fiber sheets for over 100 cycles.

I. INTRODUCTION

We developed a novel gripper (see Fig. 1) for use with robotic manipulators that takes advantage of a combination electrostatic/gecko-like adhesive [1]. The adhesive allows the manipulator to pick up and release flat objects and offers several advantages over traditional vacuum-based grippers. These include no external tubing or support equipment, as required by suction cup grippers commonly found in factories, and the ability to be used for space applications where vacuum gripper usage is precluded.

Moreover, while the adhesive does require power to engage, the power consumption is extremely small relative to a vacuum gripper. For example, consider a comparable system by Shaltz Automation (Flint, MI) with Piab piGRIP® FX77T30.B3.S1.G38M.01 vacuum cups that require 80–95psi of compressed air at 17.5 CFM. The retail cost is over $3,200; however, the cost of ownership is much higher. Assuming 4 true cfm at 100psi per HP [2] with an 80% efficient vacuum pump (this would occur upon leakage of the air system, which could be worse) coupled with a cost of 12 cents per kWh of electricity [3], the cost of running this gripper for 1,000 hours would approach $30,000. In contrast, the major source of power consumption in our proposed gripper is the required high-voltage DC/DC converter necessary to operate the electrostatic adhesion, which typically runs on the order of hundreds of milliwatts, which results in a cost of less than 12 cents for 1,000 hours of operation. The adhesion also will not lose its grip over time, as opposed to suction, which bleeds off. Last, the gripper’s engagement and disengagement is less than 16ms, making increases in throughput possible as well [4].

II. BACKGROUND

The adhesive used in this paper builds upon two different technologies: gecko-like “dry” adhesion and electrostatic adhesion, the combination of which was first reported in [1]. These two technologies have been combined into a single adhesive that can surpass the sum of its parts, particularly on matte finish (rough) surfaces. This section describes these two technologies individually as well as the benefits of combining the two into a single adhesive.

A. Gecko-Like Adhesives

Since the early 2000s, numerous researchers have built artificial dry adhesives inspired by geckos [6], [7]. The adhesives we use in this work are described in detail in [5], where the technical challenges of fabricating the adhesives has also largely been addressed. The adhesive itself consists of triangular wedges 20 µm at the base, 60-70 µm tall, and 200 µm wide with a spacing of 20 µm between each wedge (see Fig. 2). Similar to geckos, the adhesive is directional in that it uses asymmetric micro-structured hairs that create a high real area of contact when loaded in a preferred shear
direction. In other words, when a shear load is applied in the correct direction, the adhesive is ON in that it generates allowable normal adhesion. When the load is reversed, the adhesive releases from the surface with near zero force.

Features of the adhesive include the ability to affix to a wide variety of substrates including glass, metals, composites, and painted surfaces, shear adhesion of up to 30kPa [8], and ultra fast engagement (≤16 ms) [4]. The directionality of the adhesive requires that a gripper utilize opposing pairs (or triads/quads) of the adhesive to generate the required adhesion force. By placing dry adhesive pads in opposition to one another, the gripper can attach using a slight squeeze and detach by releasing the “squeeze” [9], [10], [11].

For this work, the challenges are integrating the gecko-like adhesive into a gripper and applying the appropriate loads to take advantage of the adhesive’s unique properties.

B. Electrostatic Adhesive

Electrostatic adhesives are applicable to a wide range of substrate material composition and roughness. However, electrostatic adhesion is generally relatively low compared to other adhesive technologies such as suction or electromagnetism [12]. The technology has been used previously in grippers [13] and wall-climbing robots [14].

Electrostatic adhesion uses a set of conductive electrodes deposited inside a dielectric. Applying a high voltage potential across the electrodes generates an electric field, which creates an adhesive force on both conductive and non-conductive substrates [13]. On conductive surfaces, electrons are free to migrate toward the positive electrodes and form electron holes under the negative electrodes. This essentially creates a set of capacitors in which the “plates” are the electrodes and substrate. On non-conductive surfaces, the electric field polarizes the substrate’s molecules. The adhesion force is proportional to the square of the electric field strength, which is in turn dependent on a number of factors including the dielectric constant, voltage potential, and electrode geometry [13].

In a conventional electrostatic adhesive, all electrodes are placed in a single plane, as shown in Fig. 3, where the high and low voltage electrodes are arranged side by side. The gap between the electrodes is filled with a high dielectric strength material. Our previous work has shown, through both simulations and experiments, that we can optimize the electrostatic adhesive pressure by properly designing the electrode and gap widths [15].

C. Combination Electrostatic/Gecko-Like Adhesive

Electrostatic and directional dry adhesives compliment each other well. The gecko-like adhesives can generally provide high adhesion force, but they are limited to operation on relatively smooth surfaces as they have difficulty in properly engaging when the surfaces become too rough. In contrast, electrostatic adhesives work well on a wide range of materials and surface roughness. However, as mentioned earlier, their adhesion levels are relatively low. The combination of these two technologies allows us to take advantage of their strengths.

There have been several previous attempts at this including placing electrodes inside the dry adhesive microstructures [16]. However, we have shown in previous work that this is far from ideal since the geometry does not allow the electric field to disperse in the substrate [15]. Other work fabricated non-directional gecko adhesives using a conductive silicone; however, in this approach the electrodes were exposed, which limited its usability to carefully controlled laboratory environments and non-conductive substrates [17].

In contrast to the above work, our previous work in the area demonstrated a combination electrostatic/gecko-like adhesive that demonstrated strong adhesion when loaded in shear [1]. In this paper, we will expand upon that work by improving the electrostatic portion of that adhesive through a fundamental design change and a new manufacturing process. We will then apply that adhesive to a gripper and demonstrate its normal adhesion strength.

III. A NEW ELECTROSTATIC ADHESIVE

A. Concept

In this section, we introduce a new electrode geometry that layers the electrodes atop each other (see Fig. 4, left) instead of placing them in the same plane, as shown in Fig. 3. This is similar to a parallel plate capacitor in which one of the plates has “holes” or gaps in it.

This design is counter-intuitive because the electric field is highest in the dielectric between the two electrodes, not
on the substrate to which the adhesive is attaching. However, note in the circled portion on the right side of Fig. 4 how the gaps allow the electric field to essentially “leak” through to the substrate. Simulations demonstrate that this “leak” can, under certain circumstances, create a stronger electric field than the conventional design. This is because the new design allows one to decrease the gap between electrodes significantly, and gap size has a strong effect on adhesion pressure \[15\]. Smaller gaps are possible because the new design employs a dielectric with a high voltage breakdown constant (e.g. Kapton) compared to the previous design, which used silicone. Thus, less distance between electrodes is needed to prevent shorts from occurring.

From a manufacturing point of view, the new double-layer design is much simpler to fabricate than the single-layer design. Notably, the gap between electrodes in the single-layer design is very sensitive to any residual material, external particles, and trapped air. Furthermore, in the single-layer design, the gaps must be etched thoroughly to prevent any shorting between electrodes. The double-layer design resolves these issues since any small imperfections or incomplete etching only decrease the effective adhesion pressure as opposed to potentially causing a voltage breakdown failure.

B. Electrostatic Adhesive Force Optimization

A simulation model was developed using Comsol Multiphysics to evaluate the electrostatic force generated by a specific electrode pattern. The model was a two-dimensional cross section of a prescribed electrode configuration. The resulting electric field strength and electrostatic force were calculated directly in the software.

We optimized electrode and gap widths for inter-digital and concentric circle patterns and found that a solid electrode layer as the top layer produces the maximum adhesion pressure. The optimum dimensions for gap and width of the bottom electrodes depends on the distance between electrodes and the substrate. In general, as the adhesive moves closer to the substrate, bigger gaps and widths are preferred. For experimental testing, we based our designs on an air gap of 50\(\mu\)m, which produced an optimum gap of approximately 350\(\mu\)m and electrode width of 200\(\mu\)m.

Simulation results show the projected adhesion as a function of the distance between the adhesive and substrate (see Fig. 5), which can be used as a proxy for substrate roughness. The results indicate that the double-layer design is up to 3x stronger than the single-layered design.

IV. GRIPPER FABRICATION

A. Pad-Level

The hybrid electrostatic/gecko-like adhesive pads must be attached to the gripper such that normal loads can be transmitted. For this application, the adhesive/gripper interface consists of a hard backing tile bonded to the adhesive with a double-sided tape (3M Double Coated Adhesive Tape) (see Fig. 6). This tape has a silicone adhesive on one side and non-silicone adhesive on other side. The silicone adhesive side adheres well to the Kapton film and backing tile while the non-silicone adhesive side adheres to the copper sides of electrostatic adhesive.

The backing tile must be rigid and as flat as possible in order to ensure a large portion of the adhesive comes into contact with flat substrates. To achieve this, the backing tile is 3D printed from carbon fiber impregnated PLA to minimize...
warping over the time. A glass plate is thoroughly cleaned and a plastic film is placed on it such that no air bubbles or dust exist under the plastic film. Resin (G+ from Maker Juice Labs) is poured on the film and the backing tile is set on it. Normal pressure is applied on the tile to ensure only a very thin layer of resin remains between the tile and plastic film. The resulting product is placed under a UV lamp to cure the resin.

B. Gripper-Level

The gripper mechanism utilizes a set of three hybrid electrostatic-gecko pads arranged in a triangular configuration (see Fig. 7) We arranged the adhesive pads in triads to achieve a gripper that was robust to side load from any direction (as opposed to using only two opposing pads).

A proven tendon-based gripper design was based on prior work [18]. The pads are loaded by a tendon, which transfers the applied force to the center of the adhesive pads to reduce the moment load applied to the pads.

For ease of integration with industrial robots, the gripper’s tendons are actuated with a Schunk EGP 40-N-N-B two-finger parallel gripper. A five-bar linkage transfers the motion of the two parallel fingers into kinematically constrained vertical translation away from the Schunk (see Fig. 7). The load transfer pin transfers the load from the Schunk to tendons through the “load distributor.” To control the maximum load on the tendon and prevent them from breaking, a stack of Belleville disc springs are added in series to the load distributor. A wave spring is also placed in parallel to the mechanism as a returning spring to maintain release action. The load transfer pin is placed at the center of a compliance system that allows the engagement pin to float while also transferring loads. To release the load, the tension in the tendons is removed.

For the fibular stalks of the gecko adhesive to take hold between the adhesive pads and the contact surface, a consistent and compliant engagement mechanism is necessary. In our design, a ball joint bearing is used to allow the gripper body and the pads rotate. This helps align the pads to the substrate with a misalignment of up to 20°. To improve the flexibility of the pads, they are connected to the gripper body through a foam backing layer. The foam also absorbs any preload as
A prototype gripper was experimentally validated to characterize the normal adhesion force and also demonstrate repeated usage in an industrial setting.

A. Adhesion Characterization

Gripper characterization experiments were conducted using the test set-up shown in Fig. 8. In the experiments, the electrostatic adhesive was activated using a 6kV potential generated with an EMCO CB101 DC-DC high voltage converter. Note that because of difficulties in modeling the surface roughness of the substrate materials, we do not directly compare the simulation results with the experimental results. Instead, the experimental results are designed to demonstrate the overall effectiveness of the gripper.

The experimental procedure is as follows:

1) Attach the test material to wooden backing plate and place on a JR3 force/torque sensor. If the test sample was flexible (e.g. a fabric), then only the outer edge of the sample was taped to the wooden backing plate.  
2) Place the gripper on the sample by hand and apply enough preload to ensure that all pads are in contact with the sample substrate.  
3) Actuate the Schunk to engage the gecko-like adhesive.  
4) Turn on the high voltage DC-DC converter.  
5) Pull the gripper vertically from the substrate by hand.  
6) Measure the resulting force profile with Labview.

The maximum adhesion pressure of the gripper is calculated by dividing the maximum force from sensor data by the total surface area of the three pads. We performed ten tests for each sample. Figures 9 and 10 illustrate the median value of normal adhesion pressure for the gripper using the combined electrostatic/gecko-like adhesive and a gecko-like adhesive alone as a control. The error bars represent the 1st and 3rd quartile of the results.

The results show that the electrostatic adhesion improves the gripper performance in almost all cases, and its effect on flexible samples is quiet pronounced. The only exception is Mylar, but we have no clear explanation for this anomaly at this time. Also note that the repeatability of the experiments, as represented by the error bars, is a reflection of the fact that these tests were performed manually.

B. Performance Evaluation on Industrial Robot Arm

To demonstrate the usability of the gripper in an industrial setting, we mounted the gripper to a Fanuc LR Mate 200ic manipulator arm and performed more than 100 repeated pick-and-place operations. The gripper successfully performed this material handling exercise with both glass and carbon fiber plates (see Fig. 11).
The experiments were performed multiple times with no indication of performance degradation. The designed compliance of the gripper proved to be functional and useful since the pick-and-place of the plates were performed without specifically aligning the substrates and adhesive pads. Note that the experiment was performed open-loop (position controlled) and adequate preload was achieved by manual visual inspection of the gripper on the test target. The speed, acceleration, and operation time was limited by the robot and Schunk gripper capabilities.

VI. CONCLUSIONS

An industrial gripper for manipulator-arm robots that utilized an electrostatic/gecko-like adhesive was designed for pick and place operations. The gripper uses three adhesive pads loaded in shear using a Schunk gripper. A novel electrostatic adhesive design was fabricated and tested. The performance of the gripper on flexible and rigid materials demonstrated that the electrostatic element increased adhesion, especially when adhering to flexible materials. The experimental results also show that the gripper, in conjunction with a Fanuc manipulator arm, is able to successfully pick up and release glass and carbon fiber sheets for over 100 cycles. Future work will evaluate the gripper in more challenging industrial environments where dust mitigation will be an important factor, develop a non-tendon based gripper design, and implement closed loop control of the robot with a grip-sensing system.

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