A Robot that Climbs Walls using Micro-structured Polymer Feet

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Abstract

Insect-inspired foot materials can enable robots to walk on surfaces regardless of the direction of gravity, which significantly increases the functional workspace of a compact robot. Previously, Mini-Whegs™, a small robot that uses four wheel-legs for locomotion, was converted to a wall-walking robot with compliant, conventional-adhesive feet. In this work, the feet were replaced with a novel, reusable insect-inspired adhesive. The reusable structured polymer adhesive has less tenacity than the previous adhesive, resulting in less climbing capability. However, after the addition of a tail, changing to off-board power, and widening the feet, the robot is capable of ascending vertical surfaces using the novel adhesive.

Keywords: small insect-inspired adhesive wall-climbing robots

1 Introduction

Robots that could climb smooth and complex inclined terrains like insects and lizards would have many applications such as exploration, inspection, or cleaning [1]. Cockroaches climb a wide variety of substrates using their active claws, passive spines, and smooth adhesive pads [2]. Beetles and Tokay geckos adhere to surfaces using patches of microscopic hairs that provide a mechanism for dry adhesion by van der Waals forces [3]. In-

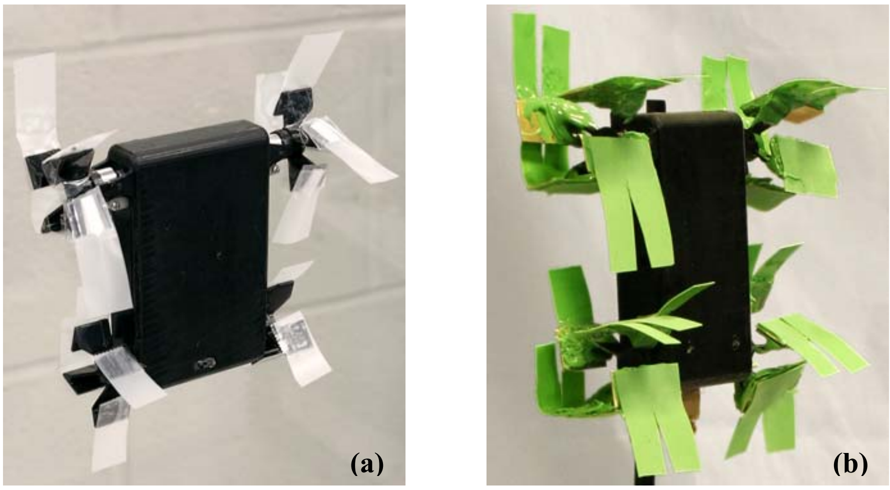


Fig. 1. Mini-Whegs™ 7 on vertical glass (a) with office tape feet and (b) with micro-structured polymer feet and 25 cm long tail (tail not shown).

spired by these animal mechanisms, new adhesives are being developed [4][5] and robots are needed to test them. Waalbots, for example, test various climbing mechanisms using traditional adhesives in preparation to testing biologically inspired adhesives [6].

Observations of insects can also provide inspiration for the kinematics of the legs of a robot. Flies make initial contact with the entire broad, flexible attachment organ (pulvilus) [7]. A slight shear component is present in the movement, which provides a preload to the surface of the attachment device. Similar shearing motion has been previously described as a part of the attachment mechanism of a single gecko seta [3]. Minimal force expenditure during detachment is also important. Disconnecting the entire attachment organ at once requires overcoming a strong adhesive force, which is energetically disadvantageous. This principle of contact formation with the entire pad surface and peeling-like detachment has been applied here to the design of a robot with climbing ability (**Fig. 1**).

2 Mini-Whegs™

Mini-Whegs™ are a series of small robots that use a single motor to drive their multi-spoke wheel-leg appendages for locomotion [8]. The spokes allow Mini-Whegs™ to climb over larger obstacles than a vehicle with similarly sized wheels. We previously developed a Mini-Whegs™ that can be used to test new bio-inspired adhesive technologies for wall climbing [9].

Mini-Whegs™ 7 (5.4 cm by 8.9 cm, 87 grams) is power-autonomous, radio-controlled, and has a total of four wheel-legs, each with four spokes. The feet are bonded to contact areas on the ends of the spokes and the flexibility of the feet acts as a hinge between the feet and spokes. The feet contact the substrate, bend as the hub turns, peel off the substrate gradually, and spring back to their initial position for the next contact. We previously reported that this robot can climb glass walls and ceilings using standard pressure sensitive adhesives [9]. This paper describes results for that robot walking on glass walls and ceilings using adhesive feet made from office tape and the adaptation of that vehicle so that it climbs walls with a biologically-inspired material.

3 Bio-inspired Materials

Two polymer samples were tested, a smooth one and an insect-inspired surface-structured one. Both samples are made of two-compound polymer polyvinylsiloxane (PVS) (President® light body, Coltene, Switzerland). The smooth samples (thickness = 0.4 mm) were molded from a clean glass surface. The structured samples made of the same polymer were obtained from the company Gottlieb Binder GmbH & Co. KG (Holzgerlingen, Germany). The base thickness of the structured sample was approximately 0.4 mm. The protrusions were about 100 µm high and about 40 µm in diameter. Young's modulus, E, of the bulk polymer is 2.5 to 3 MPa [4].

3.1 Traction Properties On Glass

The tangential forces, *i.e.* traction, of a 1.5 cm by 3.5 cm flat sample had typical stick-slip behavior with a maximum force of 0.25 N/cm^2 and zero minimal force. For the structured sample, maximal force was 0.11 N/cm^2. After series of 3–4 trials, the flat sample no longer attached to the substrate properly. After cleaning with water, the traction ability was recovered, showing that traction of the flat sample is sensitive even to slight contamination. For the structured sample, such sensitivity to contamination was not evident.

3.2 Adhesion Properties On Glass

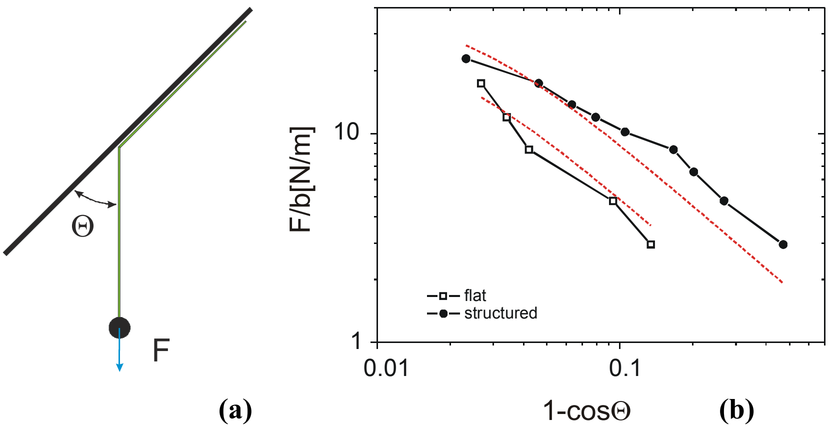
Peeling testing was performed for characterisation of adhesive properties of structured samples. Peeling is delamination of a thin film from the substrate under action of a loading force, F, acting under an angle Θ to the substrate. In the experiment, the peeling force, needed for delamination of the polymer tape (flat and structured), was measured.

PVS samples (25 mm width) were attached to a clean smooth glass surface in a horizontal position and loaded with a weight. Then, the tilt angle of the glass was increased by steps of 2.5° until peeling occurred (**Fig. 2a**). The normalized equilibrium force, F/b, is plotted versus the peeling angle, Θ, in **Fig. 2b**.

The Kendall model of peeling was applied to estimate the adhesion energy [10]:

$$\left(\frac{F}{b}\right)^2 \frac{1}{2Ed} + \left(\frac{F}{b}\right)(1 - \cos\Theta) - R = 0 \tag{1}$$

where F is the peeling force, d is the thickness of the adhesive, b is the width of the tape, E is the elastic modulus of the film material, Θ is the peeling angle, and R is the energy required to fracture unit area of an interface. The adhesion energy, R, for the structured material was 0.90 J/m^2 and 0.49 J/m^2 for the flat material. These tests demonstrate that structuring does benefit the polymer's adhesion at this range of peeling angle. However, similar testing of new Scotch® tape yields approximately 16 times the adhesive of the structured polymer.



(a) (b)

Fig. 2. (a) Diagram of the peeling experiment. (b) Normalized equilibrium force, F/b, versus peeling angle, Θ, for flat and structured materials. Dashed lines indicate fit corresponding to Kendall's model of peeling [10].

4 Robotic Climbing Failure Modes

There are two fundamental modes of failure for a surface-climbing robot. First, the robot can slip along the substrate due to insufficient tangential (traction) forces. Second, there may be insufficient normal (adhesive) forces, causing the robot to tumble away from the wall. Support behind the back axle (*e.g.* a tail) can reduce the likelihood of tumbling while increasing the tendency of slipping.

The vehicle falls backward from the wall when the feet on the front axle are not tenacious enough to support the normal force, N_1, required to balance the moment of the weight. By summing moments about the rear foot contact point (**Fig. 3a**), the magnitude of N_1 for a vehicle without a tail is

$$N_{1_{NoTail}} = \frac{hW}{a} \text{ (tensile)} \tag{2}$$

Therefore the 0.23 N of normal force is required for the 87-gram robot, with $a \approx$ wheelbase of 7 cm, and $h \approx$ leg length of 1.9 cm. Since the supportable normal force decreases with peeling angle, the critical position occurs when the wheel-hub on one side has just peeled up one foot and has not yet applied the next foot. At that instant, the foot on the other side of the axle must be capable of supporting the moment of the robot's weight otherwise the robot will rotate away from the wall, inhibiting proper foot

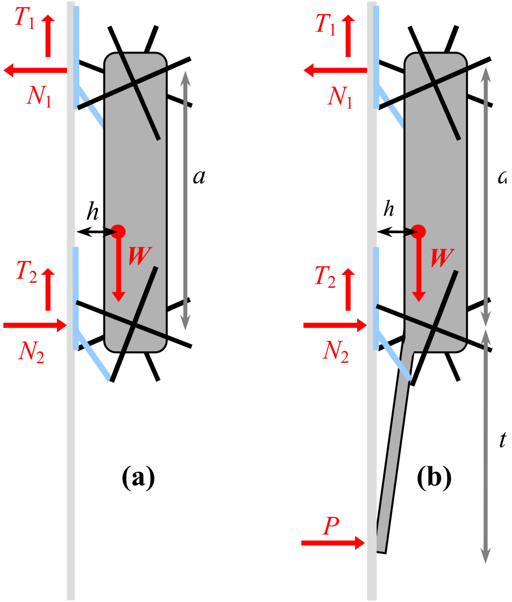


Fig. 3. Free body diagrams of (a) robot without tail and (b) robot with tail on vertical surface.

placement. Because the feet are out of phase by 45°, this should occur when the peeling foot is parallel to the substrate. From video of the robot with Scotch® tape feet, the average peeling angle at that instant is 60° (SD = 5°, n = 6). Using Equation (1), for the structured polymer the force per unit width is 0.018 N/cm. The component in the normal direction is 0.016 N/cm, which would require the feet to be at least 14 cm wide.

However, if a tail is added, the normal force, *P*, at the tail/wall contact point can aid the adhesive in countering the moment of the weight. By summing the moments about the rear foot contact point (**Fig. 3b**), the required adhesive force from the front feet is

$$N_{1_{WithTail}} = \frac{hW - tP}{a} \text{ (tensile)} \tag{3}$$

Thus, the robot with a tail will require less normal force to prevent it from tumbling backwards on a substrate, assuming a lightweight tail.

The disadvantage of the tail is that it decreases the traction forces that prevent the robot from slipping. Because the adhesive materials are pressure sensitive, the tangential forces are largest when the normal forces are most compressive. For the robot without a tail, the rear normal force, N_2, will always be equal and opposite the front normal force, N_1:

$$N_{2_{NoTail}} = \frac{hW}{a} \text{ (compressive)} \tag{4}$$

For a robot with a tail, the sum of the forces N_1 and N_2 must be equal and opposite to *P*, and from Equation (3):

$$N_{2_{WithTail}} = \frac{hW - (a+t)P}{a} \text{ (compressive)} \tag{5}$$

Thus, N_2 with a tail is always less than without a tail. If the tail is long and stiff enough, N_2 can actually be in tension. Reducing the contact force decreases the available traction, which may cause the robot to slip.

5 Robot Performance

The performance with office tape demonstrates the potential of future adhesive climbing robots. With office tape, no tail was needed and the robot (87 grams) was able to climb reliably enough to test steering, obstacle climbing, and ceiling walking. The vehicle walked up, down, and sideways on vertical planes of glass using Scotch® tape feet. Further, the robot walked inverted all the way across the underside of a 30-cm-long horizontal surface. The vehicle also demonstrated successful transitions from the floor to a vertical wall and from a wall to the floor. Gradual steering was accomplished. In a test to demonstrate climbing distance, the robot ascended a 70 cm vertical surface four consecutive times at a speed of 5.8 cm/sec, without falling, a total of 280 cm. Afterwards, the robot fell with increasing frequency as the tape became dirty or damaged [9].

When the 1.6 cm wide tape was replaced with the same size pieces of polymer and the batteries were removed, the 76-gram robot was able to climb an incline of 50º, but fell backwards from the substrate at higher angles. By adding a 6.6 cm tail and widening the front feet to 2.6 cm, the robot (at 110 grams) was able to scale a 60º incline reliably. It scaled the entire length of the incline (39 cm) at a speed of 8.6 cm/sec. The robot made 13 similar-length runs without requiring washing, lasting 1.8 times longer than Scotch® tape. Reversing the driving direction on the wall resulted in the robot falling and catching itself on the substrate.

By lengthening the tail to 25 cm and widening the back feet to 2.6 cm, the now 132-gram robot was able to climb a vertical glass surface (**Fig. 1b**). With the tail and widened feet, the robot can be placed on a vertical surface and rest indefinitely. Walking on the vertical surface was less reliable than with the tape: the robot would slide or lose traction on the substrate 44% of the time (n = 16). In the trials in which the robot did make progress, the robot walked an average of 18 cm. The longest walk was 58 cm long (the entire length of the surface) at 2.3 cm/sec. The polymer feet retained their traction/adhesive properties for several hours of testing and could be renewed by washing with soap and water.

6 Discussion

The ability to transition between orthogonal surfaces, steer, and overcome small obstacles is feasible for a robot with compliant adhesives, as demonstrated by the Scotch® tape feet. A lighter robot would be more stable on the substrate, allowing more complex maneuvers. In addition, a lighter robot may not need a tail, which can get in the way of transitions. With a body flexion joint, the robot may even be able to make transitions around more difficult external angles [11]. Mounting the axles farther away from the wall than the center of mass would allow more space for longer spokes and feet without losing stability. The addition of frictional material on the tail of the robot, where the normal forces are compressive, may reduce the tendency to slip down the substrate.

While the current robot only walks on clean smooth glass, a practical climbing robot would be able to traverse rougher surfaces as well. This will require the adhesives to be resistant to dust and oils. Additionally, alternative attachment mechanisms, such as insect-like claws or spines, could be added to take advantage of surface roughness.

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