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A Small Wall-Walking Robot with Compliant, Adhesive Feet[1]

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***Abstract* – The ability to walk on surfaces regardless of the presence or direction of gravity can significantly increase the mobility of a robot for both terrestrial and space applications. Insects and geckos can provide inspiration for both novel adhesive technology and for the locomotory mechanisms employed during climbing. For this work, Mini-Whegs™, a small quadruped robot that uses wheel-legs for locomotion, was altered to explore the feasibility of scaling vertical surfaces using compliant, adhesive feet. Modifications were made to reduce its weight, and its legs were redesigned to enable its feet to better attach and detach from the substrate, mimicking homologous actions observed in animals. The resulting vehicle is self-contained, power-autonomous, and weighs only 87 grams. Using pressure-sensitive tape, it is capable of walking up a vertical surface, walking upside-down along an inverted surface, and transitioning between orthogonal surfaces.**

Index Terms* – *Biologically inspired robotics, wall-climbing robots, adhesive-based climbing vehicles.

I. INTRODUCTION

The ability to negotiate a surface regardless of the direction of gravity significantly expands a robot's functional workspace. A robot capable of traversing non-horizontal paths is able to attain otherwise impossible goals. A small climbing robot can overcome large obstacles by walking up and over them, or it can access a high vantage by ascending vertically. Rather than restrictions based on the scale of the robot, the limits are on the distance the robot is able to travel. A compact, climbing robot can outmaneuver a large robot in tight spaces and surmount larger obstacles than a walking robot. The resulting increased versatility is valuable for stealth and range of exploration. For example, a small climbing robot can locate people trapped in the rubble of fallen buildings, or navigate difficult-to-access systems. A robot capable of functioning on any surface of a structure can be valuable for surface-based operations such as cleaning, painting, and inspection. Furthermore, a robot's ability to locomote on and anchor itself to a work surface is a critical requirement for micro-gravity operations, such as on an orbiting platform.

Robotic climbing techniques have been developed for specific surfaces. By finding randomly placed handholds, LEMUR II can autonomously climb near-vertical environments [1]. Ferrous surfaces can be climbed with electromagnetic effectors [2]. Clean, featureless surfaces can be scaled using suction pads [3][4], but compressed-air systems are bulky and the speed of the robot is limited by the speed at which the suction cups can be applied and released. Reconfigurable Adaptable MicroRobots [5] are able to traverse a wide range of surfaces by crawling or flipping, but require external power and control to run an onboard suction system. There are also surfaces on which suction-based climbing is not effective, e.g. bumpy, perforated, or dirty surfaces. Additionally, suction-based climbing cannot work in a vacuum, which restricts its application in space.

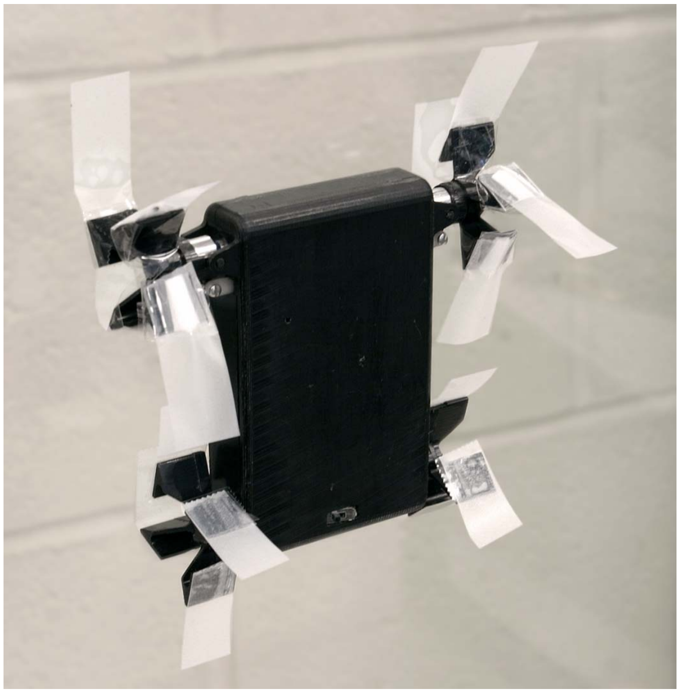

Fig. 1 Mini-Whegs™ ascending a vertical glass surface.

Insects and geckos climb a wide array of complex substrates using intricate adhesive mechanisms. The cockroach *Periplaneta americana* has compliant claws and sticky pads on its feet that facilitate climbing on a variety of surfaces [6]. The feet of the cricket *Tettigonia viridissima* bear similar surface-conforming attachment pads whose adhesive force is augmented by a secretion, allowing the animal to stand or walk on smooth vertical surfaces [7]. Tokay geckos have feet covered with millions of microscopic hairs (setae)

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that provide a mechanism for dry adhesion by van der Waals forces [8].

Using bio-inspired adhesive technology [9], a robot could potentially be developed to traverse a wide variety of surfaces, regardless of the presence of air pressure or the specific material properties of the substrate. Robots using such adhesives might some day be able to climb uneven, wet surfaces. Waalbots are a series of proof-of-concept vehicles that climb using traditional adhesives (foam tape and Silly Putty®) with treads, rigid three-spoked rotary feet, or a compliant spine [10]. These robots can reliably ascend inclines of up to 60°, but often detach from the substrate when attempting vertical surfaces.

The attachment abilities of animals on smooth surfaces are associated not only with the micro- and nanostructure of the adhesive, but also with the global scale kinematics responsible for contact formation and release. Previous studies have revealed that the manner of foot placement on the surface is an important factor contributing to the adhesive contact formation in tree frogs [11], insects [12][13], and geckos [14][15].

The most important observation from numerous insect experiments is that foot movements during contact formation are completely different from those during contact release. For animals with hairy attachment devices, such as geckos and flies, foot motion is critical in order to attach tenent setae to the substrate. Flies form the contact with the entire attachment organ (pulvilus), the shape of which resembles a piece of tape attached on one side to the leg [13]. A shear component is present in contact formation, providing a preload to the entire surface of the attachment device. Similar shear movement has been described as an aspect of the attachment mechanism for the single gecko seta [16].

For animals, the ability to detach the foot with minimal force expenditure is as important as generating strong adhesion. If the animal tries to detach the attachment organ all at once, it will have to overcome a strong adhesive force. This method of detachment is energetically disadvantageous. Using high-speed video recordings, three detachment modes of the fly pulvilli have been described, which presumably allow detachment with a minimum pull-off force. All means of detachment in the fore-, mid-, and hindlegs employ peeling either at the global scale, when the entire attachment pad is peeled off the surface, or at the local scale, when single spatula of tenent hairs are peeled off [13]. For the gecko seta, computational results show that the peeling-off force at 90° is an order of magnitude smaller than the peeling-off force at 30° [14], suggesting that the gecko would use peeling for detachment. This is consistent with observations of gecko motion [15]. The gecko has evolved special muscles and a joint design that permits the peeling action required for detachment. The principle of contact formation with the entire pad surface and peeling-like detachment seems to be a general principle for animals walking on smooth walls and ceilings.

The actuators and control required to closely mimic motion of the many joints on insect legs are too heavy and bulky for a wall-climbing robot using current technology. Several simpler robotic leg designs have been developed to reduce the number of joints and actuators. For example, PROLERO has six legs, each driven in a circular arc by individual motors [17]. RHex also uses a total of six motors to independently rotate each of its legs, but its design incorporates compliant legs [18]. Whegs™ (patent pending) takes the idea of reduced actuation one step further. A single drive motor powers four or six multi-spoke appendages called wheel-legs [19][20]. The use of one large motor provides a high power-to-weight ratio, making Whegs™ highly energetic. Mini-Whegs™ are a series of small (approximately 9 cm long) robots that use wheel-legs for locomotion [21][22]. These robots have run at sustained speeds of over 10 body lengths per second and have run over obstacles higher than the length of their legs. Some have been specialized for jumping [23] or flying [24].

The goal of the research presented here is to develop a Mini-Whegs™ vehicle that mimics the foot kinematics of insects, in order to test new bio-inspired adhesive technologies for wall climbing. In the interim, traditional adhesives can serve as a functional substitute for bio-inspired adhesives currently under development. The resulting self-contained, power-autonomous robot attaches and detaches its feet in a similar manner to climbing animals. The resulting vehicle is the first, to our knowledge, that can reliably climb walls and walk on ceilings using adhesive feet (Fig. 1).

II. DESIGN AND METHODS

In order to function as a test platform for future adhesives the robot must be capable of climbing vertical surfaces with conventional adhesive (office tape). Secondary objectives for the vehicle include maneuverability, overcoming small obstacles on the vertical surface, traversing surfaces of any orientation (e.g. ceilings and inclines), and transitioning between intersecting surfaces. An existing robot, Mini-Whegs™ 7, was modified with new legs and lighter electronics.

A. *Vehicle Design*

Mini-Whegs™ 7 measures 5.4 cm by 8.9 cm and has two axles (7 cm wheelbase) apart to accommodate a total of four wheel-legs. Both axles are driven by a single motor. A rack and pinion steering mechanism pivots the front wheel-legs. The radio receiver, drive train, and steering elements are enclosed in a Delrin® body [23]. The robot's electronics were modified so that the robot's batteries are contained. The new robot, including new wheel-legs, weighs 87 grams.

B. *Static Analysis of Vehicle*

While a static analysis doesn't take into account the acceleration inherent in the discrete steps of a wheel-leg, the following equations demonstrate some of the relationships between parameters when the robot is moving slowly or is stopped on a wall. The forces on a vehicle walking with compliant adhesive feet on a vertical wall are shown in Fig. 2. The total force applied to the front wheel-legs is T_1 tangential to the surface and N_1 normal to the surface. The back feet apply similar forces, T_2 and N_2. The distances a_1 and a_2 are from the center of mass to the equivalent centers of force of the front and rear feet. Because the feet are flexible, the forces on the rigid robot act on the tips of the spokes. However, for simplicity, these forces are assumed to act at the wall. The weight W of the robot acts at a distance h from the wall. From summing these forces and their moments, the normal force N_2 must be compressive and the force N_1 is

$$N_1 = hW/\left(a_1 + a_2\right).$$

Assuming the tangential forces of the adhesive feet are sufficient to support the weight of the robot, the maximum normal force N_1 is the limiting condition of the robot's wall-walking ability.

If $\left(a_1 + a_2\right)$ is approximated by the wheelbase, then the maximum weight of the robot is

$$W = \frac{N_1 \cdot \left(wheelbase\right)}{h}.$$

This equation predicts a smaller h (shorter leg length) will improve the chances of success. For future robots, the weight can be increased if the wheelbase is increased proportionally.

This analysis suggests that, for vertical surface walking, only the upper (front) feet require adhesive. However, adhesive on the lower feet aids in walking in different directions on vertical surfaces or inverted, provides traction when transitioning between surfaces, and helps prevent slipping.

C. *Spoked-Appendage Design*

The foot and ankle of the spoked-appendage are one flexible piece of tape bonded to a rigid Delrin® hub. This simple coupling of the legs to the axles facilitated the testing of different foot designs on the same hub. The elasticity of the foot eliminates the added complexity of a hinged ankle.

Although previous Mini-Whegs™ had hubs with three spokes, for this application, four spokes reduce the required elastic bending of the ankle from 120º to 90º. Additionally, preliminary testing indicates that the maximum normal adhesive force supportable by Scotch® Magic™ tape decreases with increasing peeling angle. With four-spoke wheel-legs and a diagonal gait, one of the front feet will always be peeling at an angle of 45° or less, whereas for three-spoke wheel-legs, this angle is 60º or less. Because the four-spoke wheel-legs have smaller peeling angles, this design provides more adhesive force.

To ensure sufficient contact area between the feet and substrate, the spoke length was chosen to maximize foot length given the existing wheelbase. A graphical model showed that a spoke length of one quarter of the wheelbase allows the longest non-interfering feet. These short spokes decrease h in the above analysis, reducing the tendency to tumble backwards off the surface. To maintain the Mini-Whegs™ alternating diagonal gait, the front left and rear right wheel-legs are in phase and offset from the front right and rear left wheel-legs by 45°.

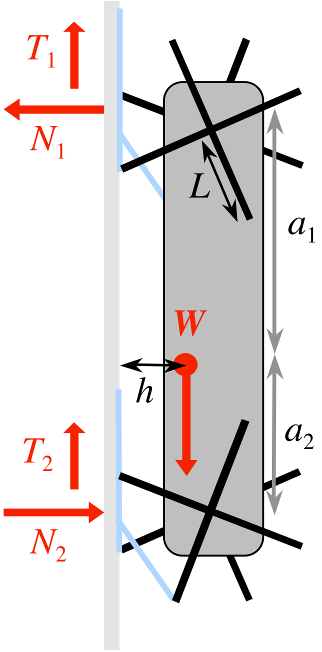

Fig. 2 Free-body diagram of a climbing Mini-Whegs™. Only feet in contact with climbing face are shown.

The orientation of the bonding surface determines the relative position of the feet to the climbing surface at contact. The interior angle between the spoke and the bonding surface of the foot is 40°. By making the angle slightly less than 45°, the feet touch the surface at the toe first and the foot flexes to absorb some of the impact. Additionally, the design includes a second bonding surface (see Fig. 3), on the forward side of the foot to allow testing of feet collinear with the spokes (see Sec. III-B). The hubs were modeled in Pro/Engineer and fabricated using a CNC milling machine from a 1.3 cm thick piece of Delrin®.

D. *Foot Design*

Traditional adhesives can support large normal and tangential forces per area. A significant force orthogonal to the substrate is required to detach the entire contact area at once. However, if the adhesive peels off the surface gradually, a smaller force perpendicular to the surface is required due the smaller instantaneous area being detached. Consequently, a flexible foot is optimal for supporting large forces tangential to the surface yet detaching with minimal motor torque.

For this design, the bond between the hub and spoke is double sided tape. During normal climbing, the feet do not detach from the hub because the tension in the tape is in the same plane as the bonding surface.

The foot needs to bend 90° elastically with each step and any permanent deformation of the material prevents it from contacting the surface properly on the next step. Since Scotch® tape springs back by itself after bending, the design was implemented with Scotch® tape alone.

Another way of altering the foot properties is by changing the profile of the tape. Curving the tape, as shown in Fig. 4,

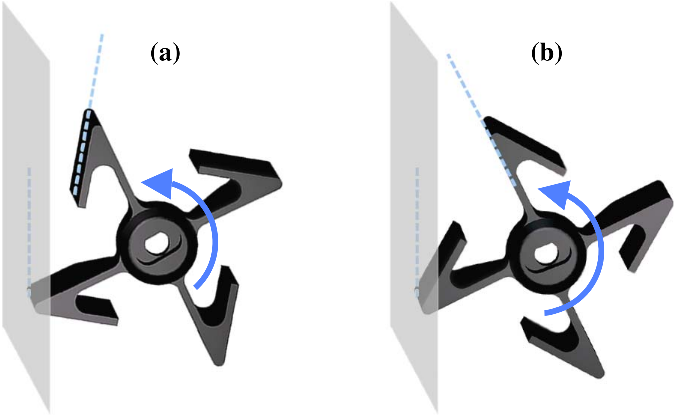

Fig. 3 Diagram of a wheel-leg with dashed lines showing the adhesive foot in a configuration (a) nearly parallel to the substrate at contact and (b) in an alternative configuration for better overcoming obstacles.

augments the stiffness up to and during contact, but maintains low torsional resistance as the spoke rotates. The center of the tip of the curved surface contacts the glass first and the entire foot is progressively flattened onto the glass. This progressive flattening ensures a more consistent application of the tape. After peeling off, the tape returns to the curved shape for the next step.

III. TESTING AND RESULTS

The test environment was a smooth, clean glass aquarium at room temperature (roughly 20º C). The robot climbed up the vertical glass repeatedly until the tape became dirty.

A. Foot Performance

For climbing upward, the front feet require a stronger adhesive, while the adhesive on the rear feet can be weaker to reduce the required motor torque. Therefore, Scotch® Magic™ tape was attached to the front hubs, while the rear wheel-legs used Scotch® Removable tape. On the front legs, the tape was curved with a small roll of foam or a graduated stack of double-sided foam tape (Fig. 5). The heel was covered by another piece of tape to prevent other feet from sticking to it.

The tape feet worked as designed. The feet adhered well to the surface at the onset of the stance cycle. The tape bent during the stance cycle and then peeled from the wall smoothly. However, during operation, the tape became dirty and occasionally bent, creased, or torn. Preliminary testing indicated that reinforcing the feet with thin shim stock hindered the climbing, but improved the durability of the feet. An infrequent mode of failure was the de-bonding of the tape feet from the spokes.

B. Vehicle Performance

The vehicle easily walked up, down, and sideways on vertical planes of glass. 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. As the tape became dirty, the robot had to be driven more slowly to stay on the wall. It climbed another 140 cm at a slower speed, after which the robot would occasionally fall after the front feet failed to adhere to the substrate. After a total of 480 cm, the robot could only take a few steps between falls.

Further, the robot walked inverted all the way across the underside of a 30-cm-long horizontal surface. The vehicle also demonstrated many successful transitions from the floor to a vertical wall and from a wall to the floor. It could not make transitions around external angles. For example, the robot walks across a horizontal surface and up the side of a glass aquarium, but falls at the upper edge rather than climbing onto the top of the aquarium. Nevertheless, the robot walked around the inside of a glass aquarium, transitioning from the ceiling to the wall, and then from the wall to the floor.

Very gradual steering was accomplished. Attempting to walk over small obstacles on the vertical surface was difficult for the robot. The vehicle fell when attempting to step over a ballpoint pen (8 mm diameter) affixed to the climbing face. However, with feet affixed to the secondary contact area (Fig. 3b), collinear with the spoke, the vehicle was able to walk over the pen.

IV. DISCUSSION

A. Foot Design

The current foot design (Fig. 5) performed well, demonstrating potential for further investigation of robots with compliant, adhesive feet. The flexibility of the tape improved the attachment and removal process. Because of the low stiffness, normally weak forces from accumulated static charge can be significant enough to pull the tape toward the surface when it gets very close. The flexible tape is pressed into the glass as the arched profile flattens, which creates a strong bond between the foot and the wall.

The front feet need to be relatively long, since the tensile normal force N_1 (Fig. 2), will continually peel the flexible tape away from the wall. If a foot detaches too soon, the following foot on the hub will start peeling away from the surface before the next foot attaches.

When the Scotch® tape is replaced with bio-inspired adhesive, we expect that some of the durability problems may be solved. For example, the new adhesive should reject contaminates and function much longer without being replaced. When the mechanical properties of the new adhesive are determined, more testing will be required and the foot design may need to be altered.

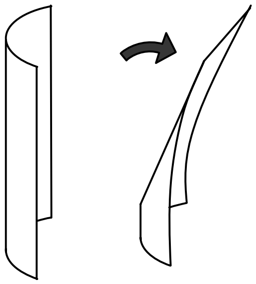

Fig. 4 Diagram of a directionally-stiffened compliant foot before and after bending.

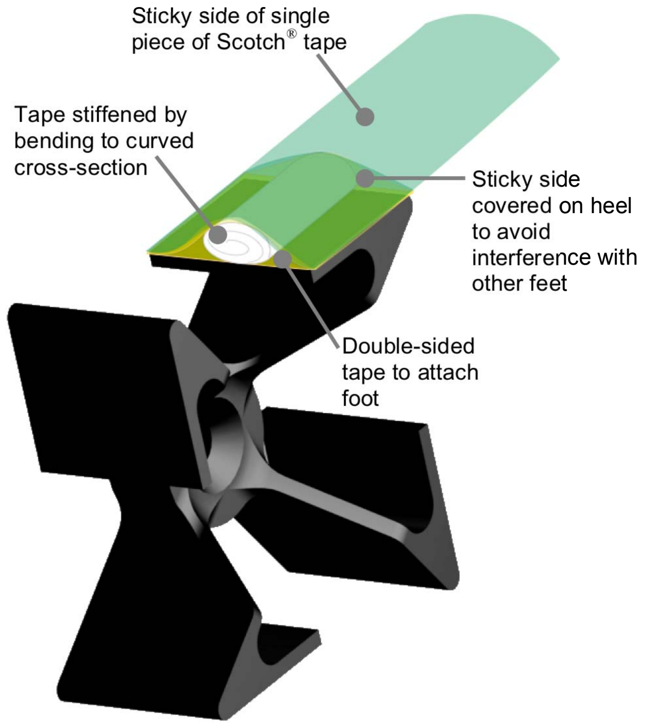

Fig. 5 Rendering of a front wheel-leg and tape foot assembly.

B. *Transitions Between Surfaces*

A useful climbing vehicle requires the ability to transition from one surface to an intersecting one. The current design is limited to transitions between surfaces that intersect at concave angles. Even these transitions were occasionally unsuccessful because they required some of the feet to be detached before the spoke was in the proper peeling position. Depending on the orientation of the spokes when the intersecting surface was encountered, the torque required to do this can stall the drive motor. Because of the flexibility of the tape, the peeling difficulty is often overcome after a slight delay. Going from a horizontal surface to a vertical surface is easier than vice versa for the robot because, as the front wheel-legs pull the robot up, the weight of the robot draws the body closer to the wall. When transitioning from a vertical surface to horizontal surface, the weight of the robot is on improperly placed feet, which increases the difficulty of peeling.

Adding a body joint [25] would greatly improve the ability to make transitions. By bending the joint before the intersecting surface was encountered, the center of mass could be shifted intentionally and the feet could be applied on the new surface earlier. The addition of a joint between the axles may also make it possible for the robot to transition around external angles.

C. *Obstacles*

Overcoming obstacles on a vertical surface is very difficult for a vehicle of this design. If the obstacle is going to be stepped over without the foot adhering, then the vehicle needs to be able to stay on the wall even if a step is missed. This vehicle can walk over a planar surface even if one adhesive foot is missing, but obstacles have the added effect of moving the center of mass away from the wall, often causing the vehicle to topple.

If the obstacle is to be stepped onto, the obstacle must be made of a smooth, clean material so the foot can adhere to it. However, regardless of material type, the foot often will not adhere to the surface of a raised obstacle because the non-sticky heel of the foot contacts the obstacle first, rather than the toe of the foot, as designed (Fig. 3a). If both front feet fail to adhere to the substrate while ascending, the robot will fall backwards. With longer spokes and shorter feet, the vehicle could overcome larger obstacles.

Having the feet co-linear to the spokes (Fig. 3b) was more successful because the toe was more likely to make contact with a raised obstacle. Since the feet must bend more with each step, the robot had to ascend slower in order to prevent the feet from creasing while operating on a smooth surface.

D. *Steering*

Because at least four of the robot's feet are attached to the wall at any given instant, steering is an extra challenge compared to previous Mini-Whegs™. In order to turn with the current design, the tape must peel off diagonally. In diagonal peeling, the length of the instantaneous area being detached is longer than during forward walking. Steering also requires that the vehicle be moving forward. If the vehicle is not moving at all, the steering servo may not be strong enough to peel the feet off. Steering too sharply can cause the tape to tear or become separated from the hub. Smaller feet, more degrees of freedom between the foot and hub, and a more powerful steering mechanism would increase the maneuverability of the robot.

V. CONCLUSIONS

We accomplished the goal of developing a vehicle to test bio-inspired adhesives for wall climbing. The modified Mini-Whegs™ can walk on inclined, vertical, and inverted surfaces and make transitions around concave corners using Scotch® tape as the foot adhesive. It performs these tasks consistently until its feet are contaminated or otherwise damaged. It attaches and peels its feet from the surface in a manner similar to that of wall climbing animals. Therefore, we conclude that the vehicle is a good test bed for bio-inspired adhesives.

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