Inchworm Style Gecko Adhesive Climbing Robot

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Abstract—We present a gecko-adhesive enabled robot that can climb surfaces in any gravitational orientation or operate in full zero gravity. The robot is a prototype for inspection applications aboard the International Space Station (ISS) both inside and outside the station. A specific area of interest for this paper is a narrow gap, approximately 1.5 inches wide, behind internal equipment racks. The prototype robot uses oppositional pairs of gecko adhesive pads that turn the van der Waals adhesion ON and OFF using an applied shear load. The robot is currently teleoperated and utilizes an inchworm style gait. The robot can turn in a tight circle, fits within a 1.5 inch gap, and can transition between orthogonal surfaces. The gecko adhesives leave no residue, are highly reusable, and create strong adhesion in vacuum and across a wide temperature range. The robot design and initial experimental results are presented including climbing vertical walls in Earth’s gravity.

I. INTRODUCTION

The In-Space Non-Destructive Inspection Technology Workshop held at Johnson Space Center in 2012 focused on several case studies including the need to inspect behind equipment racks on the ISS[1]. The gap between racks and the hull of the spacecraft is as narrow as 1.5 inches, and can be cluttered with cabling, tubing, and other infrastructure. Endoscopic and climbing robots were both proposed [2]. Future systems may combine elements of both architectures.

The Adhesive Climbing ROBOT, ACROBOT, differs from previous climbing robots that use gecko adhesives primarily in its mechanism for controlling the state of adhesion. Stickybot II [3] and Stickybot III [4] rely on gravity to load the adhesive and can only climb vertical (or slightly inverted) surfaces in a straight line in Earth’s gravity. Waalbot II [5] uses a mushroom-shaped synthetic gecko adhesive that is not directional. The adhesive is engaged by a preload force into the climbing surface and disengaged by a pull-off force. Waalbot is agile in climbing, but its profile exceeds the 1.5 inch constraint and its method of creating adhesion is not preferred for space application where preload forces are hard to generate and pull-off forces can cause a complete loss of adhesion between the robot and the climbing surface. Abigaille III [6] also utilizes mushroom shaped microfibrillar adhesives and requires a preload force. Abigaille III is designed for space applications using multiple legs that act as a base to create preload and pull-off forces in a more stable manner than Waalbot, albeit at a slower pace. Climbing MiniWhegs [7] and several tank-like robots [8], [9] similarly use pressure sensitive fibrillar adhesives. ACROBOT's adhesive mechanism couples two directional gecko pads oriented in opposition so that the adhesive can be controlled to be in the ON or OFF state regardless of the robot's orientation or the presence of significant gravity forces. The adhesive also has near-zero detachment force. Table I compares these robots' capabilities.

II. GECKO ADHESIVE BACKGROUND

Geckos’ toes consist of a hierarchy of several structures. On each toe, the gecko has tens of mm-scale flaps called lamellae on which arrays of μm-scale ‘hairs’ called setae grow. Each setae branches further into many nm-scale hairs called spatulae that make contact and stick using predominantly van der Waals forces [10]. The system conforms to the roughness of a surface and distributes loads evenly to all of the nanoscopic contacts. The setae, lamellae, and larger foot structures act as a suspension for the spatulae[11].

ACROBOT's synthetic gecko pads are composed of a two-tiered structure. A suspension layer conforms to surface roughness and compensates for small misalignments of the gecko pads. A directional adhesive layer makes contact with
TABLE I

COMPARISON TO OTHER CLIMBING ROBOTS

<table>
<thead>
<tr>
<th>Capabilities</th>
<th>ACROBOT</th>
<th>Stickybot III</th>
<th>Waalbot</th>
<th>Abigaille III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sloped Climbing</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Vertical Climbing</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Inverted Climbing</td>
<td>I.P.</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Plane-to-Plane Transition</td>
<td>I.P.</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Turning</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>I.P.</td>
</tr>
<tr>
<td>Microfibrillar Structure</td>
<td>directional mushroom</td>
<td>directional mushroom</td>
<td>symmetric mushroom</td>
<td>symmetric mushroom</td>
</tr>
<tr>
<td>Payload [kg]</td>
<td>0.2</td>
<td>1.0</td>
<td>0.1</td>
<td>?</td>
</tr>
</tbody>
</table>

Y = Yes, N = No, IP = In Progress

Fig. 2. Left, the microstructured adhesive, Center, 1000x mock up of adhesive in OFF state, Right, 1000x mock up of adhesive in ON state

The surface to generate van der Waals adhesion. The adhesive layer consists of an array of 80 \( \mu \)m tall directionally biased compliant wedges with directional mushroom tips. Fig. 2 shows the structure and its ON and OFF states. With applied shear, the wedges bend and increase the real area of contact with the surface, effectively turning adhesion ON. With no shear load (adhesive OFF), only the tips of the wedges make contact and there is near-zero adhesion. This adhesive follows the directional adhesion model [12] with a maximum normal adhesive pressure of 25 kPa and shear adhesive pressure of 80 kPa in controlled laboratory testing. It has been fabricated from several space-grade silicone materials and tested in a thermal-vacuum chamber at -60°C and at full vacuum without any loss of performance [13], tested for over 1 year under static load followed by reuse, tested on over 30 spacecraft surfaces [14], and tested to over 30,000 ON-OFF cycles [15].

III. ROBOT DESIGN

ACROBOT’s height is less than 1.5 inches during planar locomotion enabling it to fit behind the racks aboard the ISS. The robot has low mass to allow testing in a 1 g environment, and similarly, the robot’s center of mass is close to the climbing surface during all maneuvers to reduce moments applied to the adhesive pads.

A force and moment analysis was conducted, Fig. 3, for the most critical loading orientation in Earth gravity \( \theta = 90^\circ \). The sum of forces and moments about the x, y, and z axes must remain less than the van der Waals adhesion (determined through testing) as shown in equations 1-4.

\[
\sum F_x = F_{N,GP} + F_{N,T} + m_r g \sin \theta = F_{adh,x} \quad (1)
\]
\[
\sum F_y = m_r g \cos \theta = F_{adh,y} \quad (2)
\]
\[
\sum F_{z, shear} = F_s = k(\delta x) \quad (3)
\]
\[
\sum M_z = L_1 F_{N,T} - F_y (L_3 \cos \theta + L_2 \sin \theta) = M_{adh} \quad (4)
\]

The robot is designed with four primary modules to enable climbing in any orientation on Earth and in zero gravity. The Gecko Module toggles two adhesive pads between their ON and OFF states by applying a shear force. The Compliant 4-Bar Module allows the robot to orient its gecko adhesive relative to the climbing surface in three distinct task positions allowing for same-plane step sequences as well as orthogonal plane-to-plane transitions. The Inchworm Module controls the inchworm gait and steering. The Tail Module passively counteracts moments on the gecko pads due to gravity and helps preload the pads before engagement.
A. Gecko Module

Two 5x5 cm gecko pads are oriented in opposition to create an omni-directional anchor controlled by one actuator, similar to mechanisms previously described for grappling objects in space or perching with unmanned air vehicles [16]. Pads must remain coplanar (within 0.5° and 100 µm) to adhere properly. To ensure alignment, a linear guide rail and a pair of ball-bearing carriages are used.

A linear actuator (Firgelli PQ12) is used in parallel with an extension spring to actuate the module. The linear actuator extends to put the spring in tension before contact with the surface. The pads are placed on the surface and the linear actuator retracts (it is only fixed to one gecko pad) allowing the spring to maintain the applied shear load and keep the adhesive pads turned ON. To turn the adhesive OFF, the linear actuator extends to overcome the spring force and remove shear loads from the pads. Using springs to maintain tension on the gecko pads in the ON state conserves robot power and allows the robot to loiter indefinitely in one location. Fig. 4 shows the mechanism. The internal motion has a negligible effect on the robot’s center of mass.

The shear force required to produce high adhesion is dependent on the gecko pads’ area and the surface material. Based on empirical tests, a spring was chosen that could supply appropriate shear forces for a variety of climbing surface materials (e.g. glass, composites, polished metals, drywall) within the linear range of the spring, and the linear actuator was sized to provide sufficient force (35 N) and stroke (20 mm).

B. Compliant 4-Bar Module

Accurate positioning is required to put the gecko modules onto and off of the surface. For pads to remain parallel to the surface and avoid scrubbing, the optimal trajectory is a straight line orthogonal to the surface. However, the robot must also execute plane-to-plane transitions (i.e. wall to ceiling, floor to wall, wall to wall, etc.). To kinematically accommodate both maneuvers as well as consistently execute step sequences and turns, a planar 4-bar linkage was synthesized to pass through three discrete operating positions, each with a desired module orientation angle [17]. The linkage passes through two positions that approximate straight-line motion with identical orientation (pads parallel to the climbing surface) as seen in Fig. 5. The third position rotates the gecko module to an orientation orthogonal to the original climbing surface, shown in Fig. 7.

The linkage was synthesized to also allow the pads to engage the surface orthogonally within ±10° of the crank angle while remaining nearly parallel to the surface in this region. During synthesis, a constraint equation was applied to the two RR-chains forcing the solution to have a transmission angle of η = 90° to maximize preload force transmission from the crank-driving servo at task position 2. The Gecko Module’s three states are described by a set of planar transformation matrices in the form \( T = [A(\phi), d_T] \), all relative to the fixed coordinate frame whose x-z plane is coincident with the surface. Angle \( \phi \) is relative to a line orthogonal to the gecko pads and climbing surface.

<table>
<thead>
<tr>
<th>Position</th>
<th>( \phi )</th>
<th>( d_x ) [in]</th>
<th>( d_y ) [in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Gecko Module Down (Purple)</td>
<td>0°</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2) Gecko Module Up (Red)</td>
<td>0°</td>
<td>1.0</td>
<td>0.32</td>
</tr>
<tr>
<td>3) Plane-to-Plane Position (Orange)</td>
<td>−90°</td>
<td>1.86</td>
<td>2.3</td>
</tr>
</tbody>
</table>

A compliant and anisotropic coupler link was designed to allow the Gecko Module to passively deflect and conform to slight misalignments under light preload. The novel coupler
link is soft in bending in one direction and stiff in the other due to the contact-aided design. This hard stop prevents the robot’s body from rotating away from the climbing surface. The link was fabricated using an iterative milling and casting process known as shape deposition manufacturing (SDM) [18]. SDM offers advantages in the fabrication of compliant mechanisms for its ability to yield multi-material and embedded component parts. Using SDM, the coupler link was made of a stiff urethane plastic (Task 9) that holds embedded 2 mm ball-bearings and incorporates a flexible urethane rubber section (Vytaflex 60) used as the compliant bending region of the link. A Timoshenko beam superposition model was generated to analyze the stiffness ratio for the couplers bending (without mechanical stopper) in both directions [19]. The ratio of stiffness in bending with vs. against bias was found to be $K_1/K_2 = 1/9.4$ using the deflection of the beam to calculate stiffness. The parameters that affect the difference in stiffness are the effective beam height, $h$, and beam length, $l$, which differ depending on which direction the moment is applied.

$$M = k\Delta \theta = \frac{EI}{l}(\Delta \theta) = \frac{Ei(\frac{1}{12}bh^3)}{l}(\Delta \theta)$$

$$k_{ratio} = \frac{k_{flex}}{k_{stiff}} = \frac{1}{9.4}$$

By limiting $\theta$ to $\pm 5^\circ$ with a known gravity-induced moment $M$, the link stiffness $k$ can be attained. Once determined, several coupler cross sections of various materials ($E$) were designed to achieve the desired stiffness.

C. Inchworm Gait Module

The body of the robot provides two degrees of freedom: prismatic extension and turning. A brushed 8 mm Maxon DC motor drives a micro rack and pinion to create prismatic motion (extension/contraction) between the Gecko Modules creating the inchworm gait with a maximum step size of 4.5 cm. Turning is accomplished with a servo-driven geared revolute joint that rotates (yaw) the front gecko module relative to the body and rear module (Fig. 8).

During typical forward motion with all pads adhered to start, the Front Gecko Module is first turned OFF then disengaged from the surface using the Front Compliant 4-Bar Module. The rack and pinion then extends the robot relative to the adhered rear module. The Front Gecko Module is then placed back into contact with the climbing surface under a light preload that is reacted by the back pads and tail. After the pads adhere, the rear module is turned OFF and lifted off the climbing surface using the Rear Compliant 4-Bar Module. The rack and pinion is then actuated in reverse to pull the Rear Gecko Module forward. The module is then placed on the climbing surface and actuated to the ON state. This gait, shown in the supplemental video, then repeats.

D. Tail Module

The robot’s center of mass is displaced from the climbing surface causing a peeling moment due to gravity when climbing vertically or inverted in Earth’s gravity, as represented by,

$$M_{gravity} = m_r g(L_3 \cos \theta + L_2 \sin \theta)$$

where $L_2$ and $L_3$ are shown in Fig. 3. The adhesion of a Gecko Module, shown in Fig. 10, is highest under shear and normal loads while relatively weak under applied moment loads. Moment loading can cause a peeling adhesion failure when only one Gecko Module is adhered to the surface. Therefore, to help the robot climb vertical and inverted surfaces in Earth’s gravity, a passive tail mechanism is fixed to the robot’s body and used to counteract the moment due to gravity by applying a counter moment about the set of adhered pads. Two tails are needed, one on each side, for inverted climbing. To produce a counter moment equal to the moment due to gravity, $L_1$ must be equal to $L_3 \cos \theta + L_2 \sin \theta$. However because the tail is not actuated, it cannot create additional counter moment by pushing into the wall or extending its length. Therefore a length equal to $L_3$ when the robot is in its fully extended state (most critical) was chosen for the tail length $L_3$. The tail also passively acts to provide a small preload force for the pads when turning the adhesive ON. Future tail designs may be actuated to generate larger countering moments and preload forces. The use of a third Gecko Module would also alleviate moment loads and may be used in place of tails in future prototypes.
E. Controller and Sensors

ACROBOT is controlled using two daisy chained Pololu Baby Orangutan 328 microcontrollers in a master / slave configuration. The controller powers two linear actuators, a brushed DC motor, and three servo motors. Position control of the servo motors is done using the IO ports to generate a PWM signal. ACROBOT is currently teleoperated via serial connection to a laptop computer. Code was written to manually control the robot’s actuators with 5 character string commands. Algorithms have been developed to automate step, turn, stationary adhere, and plane-to-plane maneuvers, and ongoing work will convert these pseudo-code algorithms into autonomous closed loop control using a variety of sensors already onboard the robot or planned.

ACROBOT uses two linear potentiometers to determine the position of the linear actuators. A shaft encoder on the pinion is used to determine extension and contraction lengths of the rack, and four digital micro switches sense when each gecko pad makes contact with the surface. A fifth micro switch is used as a limit switch for the rack and pinion. Hall effect sensors are being implemented on the Gecko Modules to close the loop on whether adhesion was created when attempting to turn pads ON. Physically, the sensors transduce the relative distance between pads for comparison with the potentiometer output from the linear actuator, which is only fixed to one of the pads (acts in push-only). These sensors can also sense the distance between two pads prior to engagement, which is controlled to set the applied shear force to an level that is tuned for different surface materials.

IV. Results

A. Adhesive Gecko Pad Suspension Structure

In controlled laboratory tests, the directional gecko adhesive requires almost no preload to engage [15]. However, on the robot, tolerances and manufacturing imperfections lead to slight pad-surface and pad-pad misalignments that are significant at the micro-scale of the adhesive. Using a hierarchical suspension layer and a slight preload orthogonal to the climbing surface can overcome these misalignments, however maximum adhesive performance is sacrificed. Testing of pad pairs shows adhesion strength increases with preload until reaching a critical value, presumably due to good alignment. Three suspension types were tested to simultaneously maximize adhesion strength, minimize preload, and maximize pad life.

The first suspension tested was a urethane directional stalk suspension using silpoxy glue to adhere the two layers, as developed in [20]. This suspension is advantageous because it requires little preload, but curing comparabilities of the glues and various polymer layers create stress gradients that warp the gecko layer and limit the usable life of the gecko pad to around 3 weeks. The second suspension was a directional urethane stalk suspension using double-sided silicone tape to join the suspension layer to the gecko layer. This alternative creates much stronger adhesion because the double-sided tape acts as a structural shear layer close to the surface, as in [21]. The third suspension type tested was a soft, thin cellular silicone foam using double-sided silicone tape to join the suspension to the gecko layer. This suspension created the strongest adhesion of all the types tested, and eliminated lifetime issues with the pads. Table III compares the different suspension layers.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Urethane Stalks (Glue)</th>
<th>Urethane Stalks (Tape)</th>
<th>Silicone Foam (Tape)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspension Stiffness</td>
<td>Compliant (&lt;1.2)</td>
<td>Stiff (&gt;2)</td>
<td>Medium (Tape)</td>
</tr>
<tr>
<td>Required Preload [N]</td>
<td>Normal</td>
<td>Shear/Slide Load [N]</td>
<td>Moment Load [N-m]</td>
</tr>
<tr>
<td>4.9</td>
<td>6.1</td>
<td>7.9</td>
<td>0.05</td>
</tr>
<tr>
<td>7.8</td>
<td>9.9</td>
<td>12.8</td>
<td></td>
</tr>
</tbody>
</table>

B. Gecko Module Characterization

To solve for the robot’s design parameters from equations 1-4, the maximum adhesive forces of the Gecko Modules must be known. A series of tests were conducted applying normal, shear, and moment loads onto the Gecko Module to characterize adhesive strength under varied preload conditions. The data presented in Fig. 10 are the averages of five trials taken for each preload condition. The plots indicate adhesion is preload-dependent until a critical load at which misalignment in the pads has been overcome.

The hierarchical foam suspension requires the robot to apply a preload onto the gecko modules when turning them ON. To maximize the amount of preload force generated by the robot, tests where conducted to determine what mechanisms and control behaviors contribute to generating the largest preload forces. The max applied preload force for several situations are shown in Table IV.
TABLE IV
MECHANISM VS. PRELOAD

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Preload Generated [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robot Clamped/Fixed</td>
<td>5.0</td>
</tr>
<tr>
<td>Back Pads Adhered</td>
<td>0.4</td>
</tr>
<tr>
<td>Back Pads Adhered with Tail*</td>
<td>1.3</td>
</tr>
</tbody>
</table>

*Note: A maximum preload of 3.3N was attained when the pads did not maintain alignment with the surface.

Fig. 10. Adhesion vs applied preload for a Gecko Module. Adhesion depends on preload until a critical threshold (30 N) where pads reach coplanar alignment. This currently exceeds the amount of preload that can be generated by the robot. Improved climbing performance can be realized with better initial alignment of the gecko modules.

C. Climbing Tests and Summary

ACROBOT has successfully executed several climbing tests on inclined slopes as well as full vertical planes under teleoperation. The effectiveness of the compliant 4-bar mechanism has been validated through several climbing scenarios where the pads were not initially well aligned to the surface. In these cases, the crank was rotated slightly beyond the nominal angle where the pads should theoretically be parallel to the surface. This control maneuver allows the servo-actuated crank to preload the pads into the surface and ‘force’ parallel alignment. This is possible because the compliant coupler link passively deflects under the applied load from the servo motor to allow the gecko pads to reach their coplanar alignment. Using this technique, ACROBOT is currently able to climb vertical smooth surfaces supporting its own mass (323 grams) and an additional 200 gram payload at 0.15 cm/s. ACROBOT has also been tested hanging inverted with just one or both gecko modules adhered and is able to hang indefinitely in both operating configurations. With both modules adhered ACROBOT can support its body weight and an additional 600 gram payload on fully inverted surfaces. With only one module adhered ACROBOT can only support its weight and a payload of 75 grams. Ongoing tests plan to demonstrate inverted mobility and plane-to-plane transitions. The initial robot concept and prototype test validations show promise for future climbing applications in Earth and in space.

V. ACKNOWLEDGMENTS

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