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Electroadhesive Robots—Wall Climbing Robots Enabled by a Novel, Robust, and Electrically Controllable Adhesion Technology

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Abstract—**This paper describes a novel clamping technology called compliant electroadhesion, as well as the first application of this technology to wall climbing robots. As the name implies, electroadhesion is an electrically controllable adhesion technology. It involves inducing electrostatic charges on a wall substrate using a power supply connected to compliant pads situated on the moving robot. High clamping forces (0.2–1.4 Newton supported by 1 square centimeter of clamp area, depending on substrate) have been demonstrated on a wide variety of common building substrates, both rough and smooth as well as both electrically conductive and insulating. Unlike conventional adhesives or dry adhesives, the electroadhesion can be modulated or turned off for mobility or cleaning. The technology uses a very small amount of power (on the order of 20 microwatts/Newton weight held) and shows the ability to repeatably clamp to wall substrates that are heavily covered in dust or other debris. Using this technology, SRI International has demonstrated a variety of wall climbing robots including tracked and legged robots.**

I. INTRODUCTION

RECENT events, such as natural disasters, military actions, or public safety threats, have led to an increased emphasis on robust reconnaissance robots, particularly ones traversing complex urban terrain in three dimensions. Innovative ground robots with good obstacle clearance capabilities typically use many modes of mobility such as wheeled or tracked motion [1], legged motion [2], or jumping motion [3]. However, the ability to scale or perch on vertical surfaces of buildings or other structures offers unique capabilities in military applications such as urban reconnaissance, sensor deployment, and setting up urban network nodes, as well as in civil search and rescue operations. The vertical mobility and perching abilities also have numerous commercial applications such as pipeline and tank inspection or accessing hard-to-reach areas for applications such as window cleaning [4]. In most of these cases, the use of a flying vehicle such as an MAV (Micro-Air Vehicle) represents a significant challenge in power consumption, complexity, and ability to navigate in confined spaces. There has thus been a sustained interest in wall-climbing robots that use a variety of different methods to clamp onto vertical substrates.

The most common commercially available wall-climbing robots use suction cups to create adhesion to some types of substrates [5]. Suction cups work only on smooth and non-porous surfaces, and magnetic wheel versions work only on ferromagnetic walls, both severe limitations in many cases. Other technologies that have been employed include conventional adhesive surfaces used to attach the robot to the wall. More recently, “dry adhesive” technologies that mimic gecko feet with tiny setae have been explored [6], [7]. These “dry” adhesives work using Van der Waals forces of attachment and offer good clamping forces with no residue left behind on the climbing surface. However, both conventional as well as “dry” adhesives suffer from being “always on,” which implies that they reduce their effectiveness over time by attracting dust, and require some power to overcome the adhesive forces in peeling away from the substrate during the robot motion. Another biomimetic approach that has been recently pursued is the use of an array of microspines to scale vertical walls that have some inherent surface roughness [8]. While this approach ensures good mechanical contact and is mostly independent of material contaminants or dust on a surface, it is difficult to climb on smooth surfaces with this approach. On larger scales, claws might be used for wall climbing in place of microspines, but claws may damage the substrate and are also inapplicable on smooth surfaces.

In the current work, the authors present a new invention called electroadhesion aimed at addressing some of the shortcomings of previous technologies for wall climbing robots. Electroadhesion is based on the use of compliant surfaces with patterns of compliant electrodes designed to create electrostatic forces of attraction between an object (the robot) and a substrate (building surface). Electroadhesion has been shown to operate with excellent adhesion pressures of up to 2 N/cm^2 on a wide variety of surfaces including materials such as concrete, wood, steel, glass, and drywall commonly found in and on buildings. Preliminary results also show the ability for good electroadhesive forces on damp surfaces such as damp concrete. A qualitative comparison of the relative advantages and limitations of electroadhesion versus other methods for wall climbing robots is listed in Table I.

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TABLE I
COMPARISON OF PROPOSED ELECTROADHESION
WITH CONVENTIONAL CLIMBING TECHNOLOGIES

Technology	Benefits	Limitations
Chemical adhesion (sticky feet)	Low-energy cost when not moving; quiet operation	High-energy cost when moving
Suction cups	High adhesion forces on smooth surfaces	Noisy, weaker, and energy inefficient on rough surfaces; requires separate pumping means
Synthetic gecko skin (van der Waals forces)	Low-energy cost when not moving; quiet operation	Technology not proven on many surfaces; complex peeling or high-energy cost when moving; adhesion greatly diminished by dust and possible moisture; limited lifetime; cannot climb some plastic surfaces
Claws, microspines	Low-energy cost when not moving; strong forces on soft surfaces (e.g., wood); unaffected by dust or moisture	Cannot climb glass, metal, or other smooth surfaces; leaves tracks
Electroadhesion (electrically controlled electrostatic attraction	Adheres to a wide variety of surfaces; low-energy cost when moving; quiet operation; simple, lightweight, compliant structure; can be switched off for cleaning of dust and liquids	Requires very small amounts of power (~0.02 mW/N of weight supported) to stay clamped

II. ELECTROADHESION—OPERATING PRINCIPLE AND ADHESION CHARACTERISTICS

As shown in Fig. 1, electroadhesion uses electrostatic forces between the substrate material (wall surface) and the electroadhesive pads. These pads are comprised of conductive electrodes that are deposited on the surface of a polymer. When alternate positive and negative charges are induced on adjacent electrodes, the electric fields set up opposite charges on the substrate and thus cause electrostatic adhesion between the electrodes and the induced charges on the substrate. These charges do not neutralize themselves to those on the clamp because of the trapped air gaps (with dimensions on the order of surface roughness of the substrate) as well as insulator material on the clamp. The principle of operation is similar on some materials to electrostatic chucks used to hold silicon wafers [9] or other specialized grippers for robotic handling of materials [10]. We note that the same geometry of clamp can be used to clamp to both dielectric and conductive substrates, albeit with slightly different physical mechanisms.

The clamps shown in Fig. 1 can be made in a variety of ways. High compliance of the clamp is key to being able to adhere to a wide range of substrate roughnesses. If high degree of compliance is desired, one can deposit compliant electrodes (typically carbon mixed into a polymer binder) as well as elastomeric insulators (e.g., silicones). However, it should be noted that some compliance could also be achieved by manipulating the boundary conditions of the clamps, as shown in the robot designs in Section III. Thus, more rigid materials such as metal or carbon coatings on rigid polymers such as Mylar or polyimide can also be used as the electroadhesive materials.

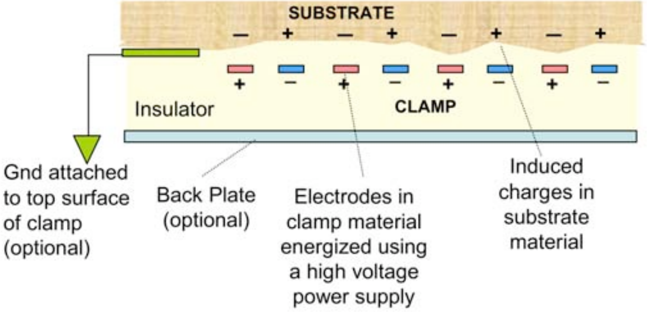


Fig. 1. Basic clamp structure for an electroadhesive clamp. Since the clamp is compliant, it can conform to the surface roughness of the substrate material.

Electroadhesive clamps are typically comprised of at least two sets of independent electrodes at different potentials. The charge on the electrodes are typically induced through the use of a high voltage power supply connected to the traces of the clamp material. We note that although the clamp material uses high voltage (typically 1–5 kilovolts), it needs very small amounts of currents (of the order of 10–20 nanoamps per Newton of lateral force) due to the presence of the insulation layer above the electrodes. Thus, commercially available low profile, low power DC-DC converters [11], [12] can be used to address the clamps.

Fig. 2 shows the clamp attached to a large variety of materials. The weight or payload that can be supported by the pad's per unit area depend on many parameters including the material properties and design of the clamp, the substrate's structure, the morphology of electrodes, and voltages used by the clamp. Table II lists the clamping pressured on typical wall substrate materials. However, we note that the concept is readily scalable to large payloads, as illustrated by a 75 lb weight held using a clamp of approximately 300 square inches of electroadhesive pad shown in Fig. 2. Thus, electroadhesion is suitable to robotic applications involving large or small payloads (with allowance for a scaled-up area for a given clamping pressure).

Since both the electrodes and the elastomer are highly compliant (through use of elastomeric materials and/or compliant boundary conditions), electroadhesive pads conform to rough surfaces (Fig. 3), enabling the electrodes to maintain a close proximity with the entire surface and thereby greatly increasing the overall clamping force. The importance of maintaining intimate contact is evident when one notes that in some regimes the electrostatic forces typically drop off as the distance squared.

Fig. 2. Electroadhesive pads clamping and holding weights up on various surfaces.

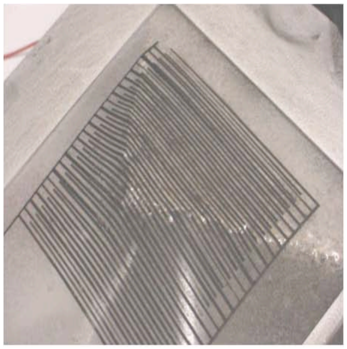


Fig. 3. Prototype electroadhesive pad conforming to a rough (concrete) surface.

TABLE II
MEASURED CLAMPING PRESSURES ON A VARIETY OF SUBSTRATES, MEASURED WITH 4 KV DC ACTUATION VOLTAGE

Material	Measured Lateral Force per Unit Area P_L (N/cm^2)	Measured Frictional Coefficient	Estimated Normal Pressure P_N (N/cm^2)
Finished wood (shelf wood)	0.55	0.4	1.375
Drywall	0.21	0.40 (estimated)	0.525
Paper	0.24	0.46	0.52
Glass	0.41	0.45	0.84
Concrete (dry)	0.17	0.57	0.3
Concrete (damp)	0.08	0.40 (estimated)	0.2
Steel	1.4	0.33	4.24

Using the clamp shown in Fig. 1, we have successfully demonstrated aspects of electroadhesion that are critical for good vertical mobility:

- High clamping pressures on a variety of substrates (wood, drywall, glass, concrete, steel, and a variety of plastics have been successfully tested to date).
- Fast clamping *and unclamping* (response time <10–50 ms).
- Ultra-low power for holding a static weight attached to a substrate (measured values are approximately 20 microW/Newton weight held).
- Ability to conform to a surface roughness, around corners, and across materials with cracks or perforations in them.
- Ability to clamp even with the presence of dust, dampness, or other surface impurities.
- Ease of fabrication using off-the-shelf components and readily integratable into both specially designed robots and even off-the-shelf robots.
- Electroadhesive clamps leave no marks on the surface (the robots can therefore be covert and non-damaging to the substrate materials).

The clamping performance for vertical holding of a weight using electroadhesion can be most easily evaluated in terms of the normal clamping pressure (P_N), the friction coefficient between substrate and clamp (μ), and the effective lateral clamping pressure (P_L). The effective lateral clamping pressure P_L is just the measured maximum lateral force without slippage divided by the clamp area. The three quantities are related by

$$P_L = \mu P_N \text{ or } P_N = P_{L.}/\mu .$$

P_L is the most important figure of merit for wall climbing, where gravity exerts a lateral force on the clamp, and it can be increased either by increasing the normal clamping pressure P_N or by increasing the friction coefficient. P_N is the most important figure of merit for mobility on ceilings where gravity exerts a normal force.

The measured electrostatic pressures on a variety of substrates are given in Table II. In some cases higher voltage can be used to significantly increase the values shown in Table II.

From Table II, it can be seen that electroadhesion exerts sufficient forces to hold up a reasonable sized robot on almost all surfaces. For example, a robot with a mass of 200 g could climb up the wall using approximately 10 square cm of clamp area in the case of damp concrete. Assuming an additional factor of safety of 4 to compensate for dynamic forces during locomotion, 40 square cm (5 cm × 8 cm, for example) of track area is sufficient for robust locomotion. As we show later in this paper, these forces and areas have been demonstrated in several realistic robots.

An additional useful feature for robotic design is the low power consumption of the electroadhesion clamps. For example, in the above case, the power to continuously hold 40 square cm of clamp has been measured to be approximately 0.25 mW on many of the substrates (power is low due to the presence of a good insulator between substrate and clamp, or because the substrate is inherently fairly insulating). This implies that with a 50% conversion efficiency, in the worst-case scenario, two AAA batteries weighing 7.6 g each can hold up a robot in "perch" mode for almost one year (calculations assume AAA primary L-92 Lithium batteries from Energizer, Inc. with a capacity of 1250 mAh at a voltage of 1.5 V). Indeed, the power draw can be even lower and batteries made to last longer with other substrates or with higher fraction of battery mass to total robot mass (in some cases, decades of perch time may be feasible). Thus, the power required for electroadhesion is a very small fraction of that required for robot locomotion, and does not represent a significantly high fraction of robot weight.

III. ELECTROADHESION-BASED ROBOTS

Because of the characteristics mentioned above, several types of wall climbing robots that employ electroadhesion can be envisioned. Indeed, electroadhesion can be used in combination with a number of climbing robots previously demonstrated. In particular, we illustrate some biomimetic and tracked robots that were implemented with electroadhesive pads.

We note that as in the case of other wall climbing technologies, resisting peeling moments is one of the major technical challenges that must be overcome in robot designs. The peeling moment comes from the fact that the center of gravity of the robot is a distance away from the wall, and tends to rotate the robot in a nose-up direction and off the wall. As with conventional adhesives, the force it takes to detach an electroadhesive pad from the wall is a sharp function of the angle of the applied load. Applying forces parallel to the clamp material tends to minimize peeling moment and maximize payload carrying ability. In some of our designs (such as the flap or double-tank versions described below), peeling is inherently minimized by the flap geometries. In other robots (such as a simple tank version), peel resistance is provided solely by the use of "tails" that are preloaded against the wall. The use of such "tails" to provide counter moments has been inspired by nature [13] and used in previous wall-climbing robots [7], [8], [14]. Where possible, the weight of the discrete robot components such as motors and batteries were shifted to the tail and close to the substrate to enable the robot body to be as flat against the wall as possible with minimum peeling forces.

A. *Tracked / Wheeled Robots*

Electroadhesion lends itself well to conventional wheeled and tracked robots and can use the inherent speed and simplicity advantages of these types of robots. In these cases, electroadhesion can be retrofitted to conventional ground robots. The most successful robot configuration that was demonstrated involves flexible electroadhesive flaps that are attached to a central drive tank as shown in Fig. 4. In this design, compliant flaps attach to the wall with very little resistance. Since the flaps are attached only at the bottom side, the force exerted by the robot on the flap is almost exclusively in shear and not in the peel direction. This kind of loading helps maximize the forces that the flaps can exert on the wall.

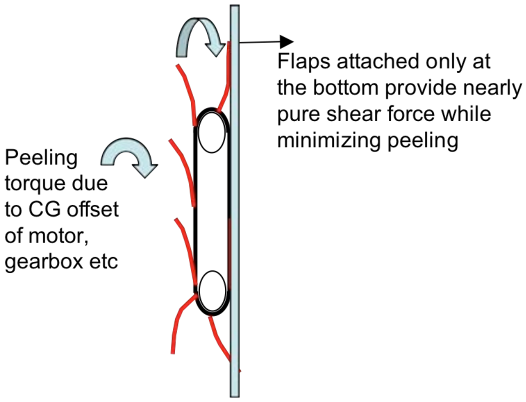


Fig. 4. Schematic of tank-type robot with flexible electroadhesive paddles or flaps. The pads are loaded parallel to their surface, thereby minimizing peel.

The tracks in this case use a chain or belt drive attached to an electroadhesive surface that can conform around rough or uneven surfaces. In this fashion, the entire robot is surrounded by an electroadhesive surface. An implementation of this robot climbing a wooden door is shown in Fig. 5. This design offers the advantage of providing a large electroadhesive surface area without requiring an appreciable normal force or intimate initial contact with the substrate (due to compliance of the flaps). In addition, this type of design offers a reliable, robust, and proven way for locomotion on unstructured terrain, and has been proven in ground-based robots with less compliant legs replacing the flaps in this case [2]. The robot shown in Fig. 5 had a weight of 180 g without onboard batteries and RC control, and weighed 220 g with onboard batteries and control. This robot was demonstrated to climb various surfaces with speeds of up to 15 cm/s. The electroadhesive tread footprint was approximately 20 cm × 12 cm (not counting driving treads located on the tail as shown). A simple brush mechanism consisting of a preloaded wire physically contacting the electroadhesive treads was used to transfer charge from the fixed robot frame to the rotating tracks as shown in Fig. 5. If necessary, a set of brushes of a commutator that charges up the tracks when they are about to contact the wall and discharges when they are about to peel away from the wall can be used to minimize peeling forces. However, such a mechanism is not necessary and was not implemented in the current configuration (one can simply use the motor drive to peel the electroadhesive track from the wall on the back of the robot). The disadvantage of this design is that in order to turn left or right, the tracks must slide relative to the surface. It may therefore be necessary to build two sets of tracks, such that the tracks can be swiveled one at a time after their electroadhesion is switched off and one of the two sets of tracks can remain attached to the wall at all times. Turning was not implemented in our first proof-of-principle robots, and will be investigated in the future.

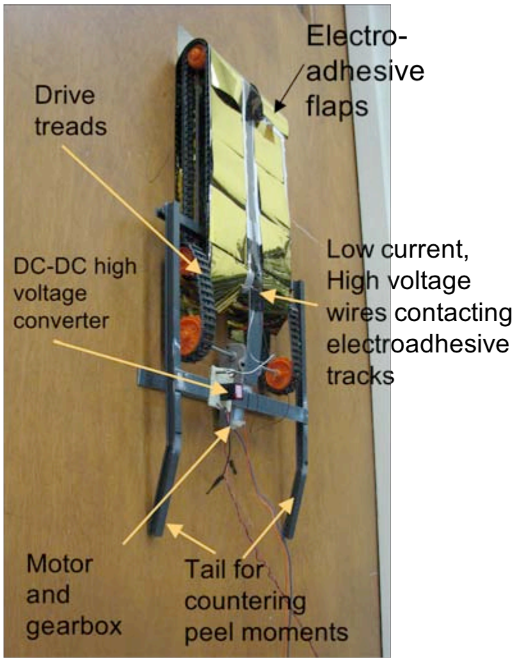


Fig. 5. Tank-type robot with flaps climbing on a wooden door. The flaps are attached to an electroadhesive surface, which is in turn attached to the tank treads driven by the motor. Power and control were offboard in this example, although other robots with RC control and onboard power were also demonstrated.

Other examples have also been successfully demonstrated at SRI. The simplest configuration involves a tank-type robot where the tread is covered with an electroadhesive surface (without the flaps from Figs. 4 and 5). However, these designs suffer from less robust peel resistance when compared with the flapped version or the double-tank version shown in Fig. 6. In this double-tank configuration, two tank robots are joined at a central pivot point. In our implementation of this double-tank design, the two tanks were fixed to each other (i.e., the pivot point was locked) and the upper tank was a lightweight, purely passive tank that provided a moment opposing peeling moments on the lower tank.

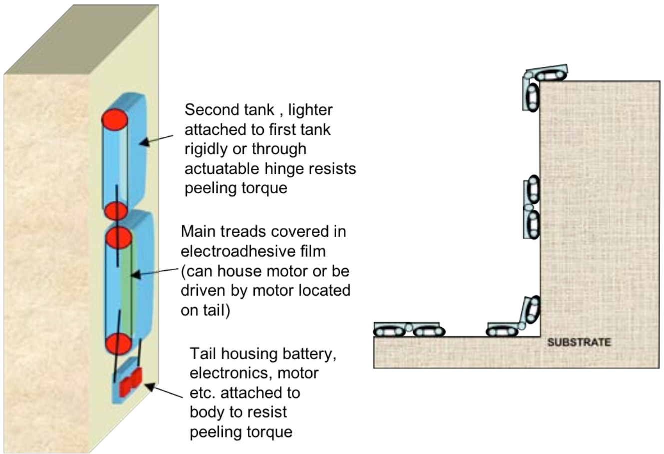


Fig. 6. Hinged double track design. Wheels are replaced by treads in order to offer greater surface area for electroadhesion.

This basic flap design can also be implemented into a fixed diameter wheel, as shown in Fig. 7. As the wheels of the robot rotate, each electroadhesive pad comes into contact with the substrate and is flattened against the wheel, providing the required clamping forces. Turning of the robot requires reduced sliding of the pads when compared with the tank design, and is a possible advantage of this design. Depending on their design, these flaps could also be used as paddle wheels for amphibious motion. Similar robot designs involving the use of flexible pads attached to rotating wheels have been successfully demonstrated for climbing robots using conventional adhesive feet [14].

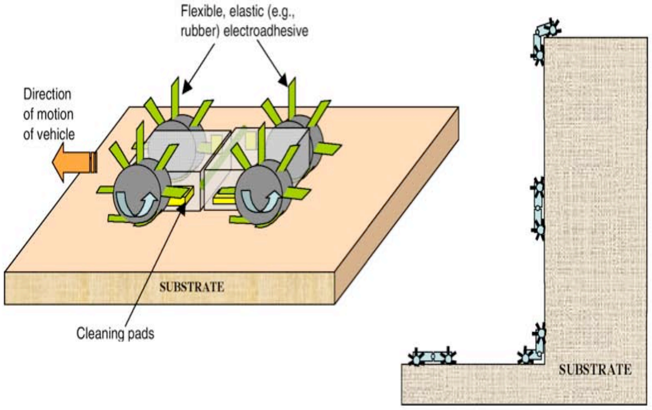


Fig. 7. Hinged flexible pad design. Each wheel on the vehicle has radial electroadhesive pads that come into contact with substrate and cause electroadhesion.

The tracks of wheeled robots as shown above were driven using conventional motor-gearbox combinations (Tamiya 72004 High Torque Worm Gearmotor) powered by conventional or high power batteries (six conventional AAA, two parallel sets of three in series). These components were typically located in the tail of the robot to minimize peeling torque due to their height. The batteries also directly powered the electroadhesive film through the use of a commercially available DC-DC high voltage converter [11], [12]. A schematic of the power flow in these robots is given in Fig. 8.

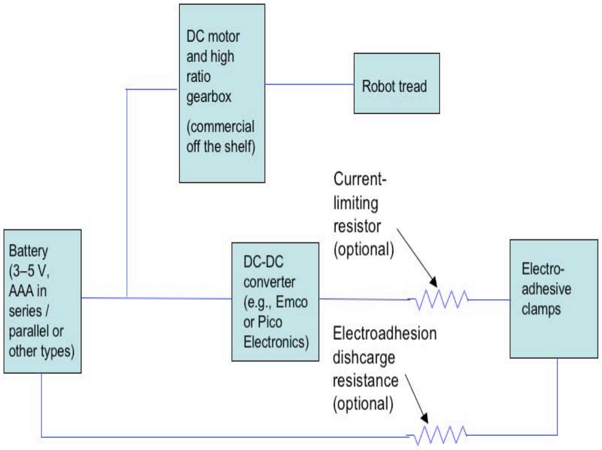
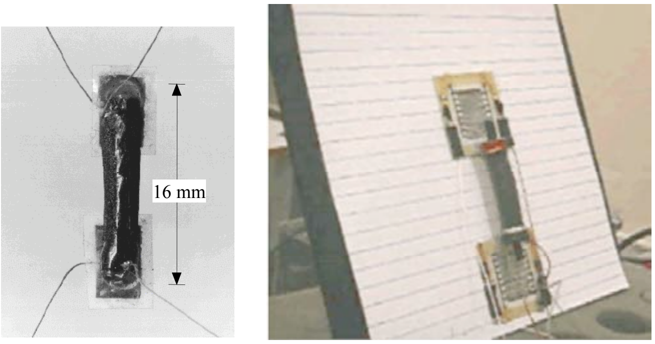


Fig. 8. Schematic of power supply to the robot and operation of electroadhesive clamps.

B. Biomimetic Robots

Since the electroadhesive clamping can be switched on and off in sequence with fast response times, the technology is well suited for a variety of biomimetic robots. For example, in conjunction with an Electroactive Polymer Artificial Muscle rolled actuator, we demonstrated the feasibility of inchworm-style wall climbing robots using electroadhesion on steeply inclined surfaces (Fig. 9). This robot used an inchworm gait (where one electroadhesive pad is clamped at a time) and was tethered. SRI first demonstrated the ability for this simple and lightweight robot to climb metallic substrates using simple electrostatic clamping (where the metallic substrate served as one of the electrodes). In this example, a robot of length 1 cm and weight approximately 20 g was demonstrated with pads of approximately 1 cm × 1 cm active area (Fig. 9a). This robot was demonstrated to travel at speeds of up to 4 cm/s (two body lengths per second) attached to metal surfaces of any orientation. In another example, the actuator and pads were designed to climb some commonly encountered paper, wood, and metallic substrate materials using electroadhesion (Fig. 9b). In this example, the roll actuator was approximately 5 cm in length, 1.5 cm in diameter, and weighed about 40 g (power to drive the multifunctional electroelastomer roll as well as the electroadhesive clamps was offboard). The electroadhesive pads had an active area of about 15 square cm each. To achieve fast unclamping, the electroadhesive clamps were driven with a bipolar AC signal (±3 kV peak, 30 Hz frequency) synchronized with actuation of the rolled actuator (5 kV square wave). Using actuation frequencies of 5 Hz for the rolled actuators, we measured climbing speeds of approximately 0.1 body length/second (1 cm/s).



(a) Older inchworm-type robot (using electrostatic clamping on metals)

(b) Newer electroadhesive robot (using electroadhesion for clamping on all materials)

Fig. 9. Prototype inchworm-type climbing robots with an electroactive polymer roll actuator coupled to electroadhesive pads that are switched on or off in sequence.

IV. CONCLUSION

Electroadhesion is a promising novel technology for wall climbing robots. It offers advantages over other types of technologies for wall climbing including robust clamping over a variety of surfaces (rough or smooth, conductive or insulating), low power, being resistant to dust, and having fast and electrically controllable clamping and unclamping. Thus, electroadhesion lends itself to a variety of wall climbing robots. Tracked "tank" type wall climbing robots, as well as more biomimetic inchworm-type robots have been successfully demonstrated to date using this technology. "Tank" type robots with electroadhesive flaps show the greatest promise for implementation into fast wall climbing robots since they minimize loading in the peel direction. Although the static properties of the clamps are well characterized and result in robust and fast wall climbing, more research is required to fully characterize the dynamic as well as peel properties of these clamps and to translate that to the dynamic mobility of the wall-climbing robots.

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