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Compliant Distributed Magnetic Adhesion Device for Wall Climbing

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Abstract – We introduce a distributed compliant device inspired in gecko foot. It consists of a holder and small independent adhesion units on a flexible support. Unlike gecko, that uses Van der Waals force to achieve adhesion, the proposed design can be based on other adhesion phenomena, (for example magnetic or electrostatic force). We evaluate an implementation based on magnets. Key features are: limited surface roughness compliance, efficiency and cost-performance.

Keywords: gecko, climbing, magnet, adhesion

I. The Need for Better Adhesion

Cheap, efficient adhesion remains a seemingly unsolved engineering problem. In wall climbing applications, reliable adhesion is a precondition for the development of autonomous robots. On the other hand, in factory automation (and particularly where mechanical gripping is not suitable) adhesion mechanisms such as (a) *suction cups* and (b) *electrostatic chuck* are used. However, in terms of maintenance and capital investment such systems come not cheap. In this text we propose an *alternative* system (inspired in gecko) that combines reliability with cost-performance. Such a system, not only would be useful for wall climbing but it might be a potential replacement for suction cups in object handling applications. In the following sections we review how and why (a) and (b) are used in industry. We introduce the concept of *distributed adhesion* and finally we evaluate an implementation of the same based on magnets.

II. Review of Two Adhesion Devices Used in Industry

A. Suction Cups

In factory automation, a widely used adhesion mechanism is the suction cup. Suction cups are used for a wide range of purposes: from handling glass windows in car assembly line to the handling of cartoon boxes in packaging lines. The popularity of suction cups is rooted in: a) its industrial-strength reliability, b) excellent grip (up to 1 atm), c) ease of use: the grip can be controlled at will by just closing/opening a valve, and d) in *delicate* applications, such as glass handling, the soft cups are better suited than mechanical gripping. However, suction cups have three main drawbacks that limit their versatility as an adhesion device: a) they require of a vacuum pump that needs periodic maintenance (operating overhead). b) Need a smooth surface. A suction cup won't work on a cylindrical object, or a rough surface like tree bark. c) Low Efficiency. The size, weight, bulkiness and power consumption of the vacuum pump seems not suited for applications where available power is limited such as in autonomous robots. [1, 2]

B. Electrostatic Chuck

Electrostatic Chuck (ESC) is a device (usually custom made) that achieves controlled adhesion by means of electrostatic forces. It is usually used in semiconductor industry to manipulate, in vacuum, delicate thin silicon wafers that risk damage and/or contamination if gripped by means of mechanical devices. A typical ESC has a shape of disc and has electrodes insulated by a dielectric material (ceramic, polymer). Characteristics of ESC are: a) It can be used in vacuum. b) Its rigidity combined with an uniformly *distributed adhesion* force do not deform thin delicate wafers, c) The high sensitivity to the surface roughness (due to the short range of the generated adhesion force) renders them ineffective in "normal" roughness surfaces (Ra>100 um) [3,4]

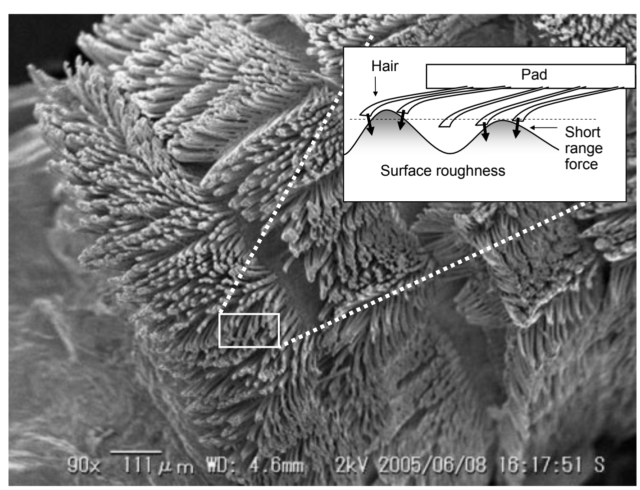


Fig. 1 Principle of gecko adhesion. The cantilever shaped hairs are compliant: a key to produce robust grip on irregular surfaces. The carpet like arrangement of the hairs allows for an energy efficient detachment by peeling. Picture: Gecko Grossmannir foot-hair.

Both, suction cups and ESC are *active* devices: adhesion can be switched on/off at will.

C. Effective Adhesion & Surface Adaptability

In suction cups, electrostatic chuck, (and other non-compliant adhesion mechanisms such as magnets, the Internally Balanced (IB) magnet [5], and electromagnets), the usual poor adaptability of the device to the substrate's surface roughness precludes effective grip on curved and/or rough surfaces. As me mentioned ESC's effectiveness, for instance, is limited to ultra flat surfaces.

On the other hand, gecko foot-hair adhesion which is based on short-range [6] forces such as Van der Waals [7] and capillary force [8] is effective in many kinds of rough surfaces. This seems due to the compliance provided by its cantilever-shaped foot-hairs. From a contact mechanics point of view, a relation between *effective adhesion* and compliance seems to exist. [9, 10]

This suggests that if a given adhesion mechanism (ESC, magnet) can be made (more) *surface roughness compliant* their effectiveness range might be expanded to more kinds of surfaces. One way to do this is by mimicking the same structure of gecko-foot hair. However, producing gecko foot-hair micro-structures (even at mm scales [10]) might be expensive (Fig. 2). Thus, one way to achieve a low cost but still reasonably compliant device might be to adopt a "striped down" version of the (compliant) gecko foot structure where *compliance* is traded for manufacturing cost.

III. The Concept of Distributed Adhesion

Fig. 3 is an adhesion device formed by a holder, and *N* distributed adhesion points (units) linked by a flexible support that provides limited surface roughness compliance. Compared to other adhesion devices this system has the following advantages:

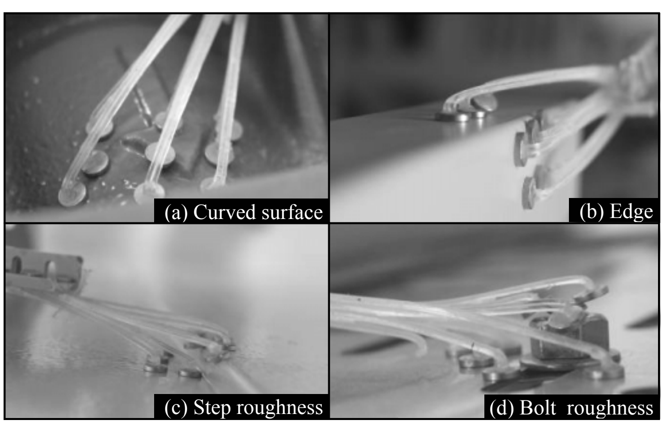


Fig. 2 Compliance of Gecko-inspired *MagneticHair.* The Van der Waals force has been substituted by magnets. The hair has surface roughness adaptability: a key factor for effective adhesion. (a)Adaptability to a curved surface: gas a pipe. (b)Adaptability to an edgy surface: a table leg. (c)Adaptability to a step: a junction of a door. (d)Adaptability to extreme roughness: a bolt.

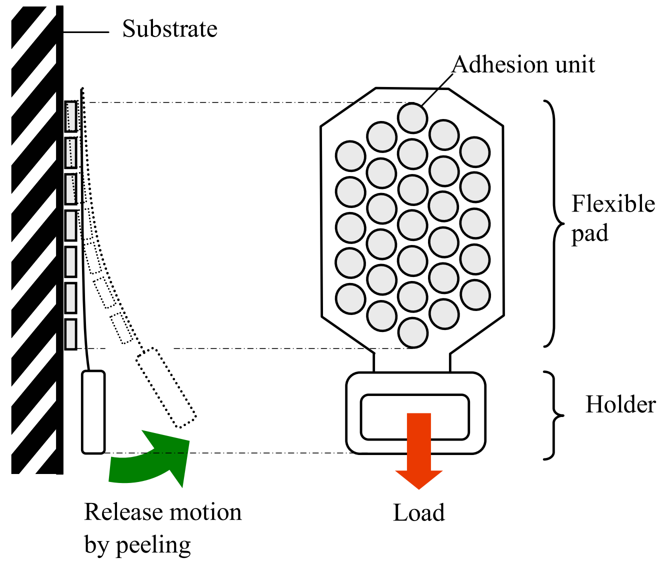


Fig. 3 Semi-Compliant Distributed Adhesion Device. The release motion is a peeling (like geckos but in opposite direction).

a) **Simplicity**. **No moving parts**.

b) **Limited Compliance**. The flexible support provides a relative degree of compliance that makes adhesion safer and more **robust** in front of surface irregularities such as: small protuberances like a bolt (in a bridge structure), or a small step-junction. The compliance allows operation in curved surfaces such as pipes.

c) All its parts operate under **tension**. Whereas IB-Magnet or suction cups have all or some parts operating under compression at some time. All parts of Fig. 3 operate under tension. This is efficient in the same way that cars with front wheel traction are more efficient than rear wheeled ones.

Main drawbacks:

a) Whereas ESCs, Suction cups, magnets and other systems have a good adhesion (grip) in a direction **normal** to the substrate, the grip of this system is weak (minimum) in the direction normal to the substrate.

b) *Active* systems such as, suction cups or ESC, have the capability of **On/Off** adhesion (at an energy expense). The proposed system, like gecko, is always on and relies on peeling motion for detachment.

A key point of Fig. 3 concept is that the adhesion units can be any adhesion device. For example: a non-compliant magnet. But, how does such a hypothetical device compare to existing adhesion solutions? Table 1, compares an implementation of the *distributed adhesion* concept (a semi compliant pad) vs three other adhesion alternatives.

TABLE I
COMPARISON OF FOUR ADHESION MECHANISMS

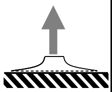
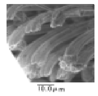
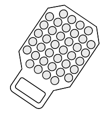
				
Device	**Suction Cup**	**Electrostatic Chuck**	**Gecko foot**	**Semi-Compliant Adhesion**
Force type	Atmospheric pressure	Induced dipoles	Van der Waals	Any
Supported surface roughness	flat & smooth	Extremely flat only [3]	Any Rough	Relatively rough, or curved
Cost	Med	High	-	Low (magnet)
Energy efficiency	Low	Med	High [11]	High
Device Weight	High	High	Low	Low
Load Capacity	Normal or Tangential		Tangential only	
remarks	Requires vacuum pump, filters	Requires kV power source	Live creature	Detachment by peeling

Table.1 Comparison of Four Adhesion Mechanisms. Pictures from left to right: 1. Suction cup schema. 2. Ceramic solid-disk Electrostatic Chuck (bi-polar type) used for wafer and plasma TV glass substrate handling (Courtesy of *Toto KK*).. 3. Gecko foot-hair 4. A compliant distributed adhesion pad

In the following section we analyze the mechanical properties of an implementation of the concept of *distributed adhesion* based on magnetic force.

IV PROTOTYPE EXPERIMENTAL DATA

Magnet-based climbing systems such as the IB-magnet [5] have been proposed in the past. However, though [5] is quite energy efficient, it is bulky and the lack of compliance prevents its use on pipes and rough surfaces in general. By applying the concept of *distributed adhesion* we can extend the usability range of hard magnet to more surface types. Fig. 4 shows a prototype of a magnetic pad used for wall mobility. Table 2 shows some mechanical data.

A. Magnetic-Pad Disposition

Each pad is composed of two parts: a hoder and flexible pad. Each pad is composed of adhesion units (44 for the hand and 72 for the foot). Each unit is composed of a toroidal rare- earth magnet semi-enclosed in an iron cup. The units are attached to a flexible support (a mm thick polypropilene sheet. The function of the cup is to shield the magnetic flux of each magnet.

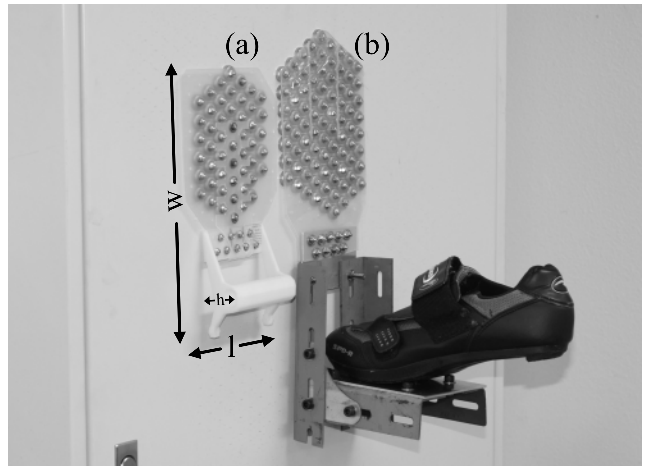


Fig. 4 Two Magnetic pads. (a) Pad for hand. The holder is realized in ABS400, the flexible pad has 44 magnets. (b) Holder for foot realized in iron angle + cycling shoe.

TABLE II
Mechanical data of ***Magnetic pad*** (hand)

Weight	**403 g**
Size	**285×150×75 mm**
Cost (materials)	**50 $**
Min Release force ($F_{Release}$[1])	**26 N**
Max Load (Typ[2]) (equiv. pressure)	**500 N** (0.15 atm)
Max Normal Grip[3] (equiv. pressure)	**75 N** (0.03 atm)

Table 2. **Data of the magnetic pad of fig. 3a**. Notes: [1]By peeling motion [2]Tested on 3mm thick painted iron substrate. [3]per pad and using a paired configuration.

In this way: (a) inter magnet mating is prevented and (b) each unit's *breakaway value* (the peak force needed to separate a unit attached to a ferromagnetic substrate) doubles. The breakaway value of a single unit is 20N. Mating is also a design constraint in living gecko foot-hair [11]

Cups have one more function: they are like claws that increase the static friction. The pad of the boot has two vertical cuts (effectively dividing the pad into "fingers"). Fingers increase the surface roughness adaptability if the substrate compliance is not high enough (thickness of the substrate is higher in the boots).

B. Detachment by Peeling & Footprint Shape

When detaching a pad by peeling, such as in Fig. 5, an initial force applied on the holder is necessary to start a *peeling crack.* We call this force F_{Start}. This force is then transmitted by the flexible support to the nearest adhesion units (1st peeling line in Fig. 5). Each unit then starts a detachment first by slight rotation and then separation (described in detail in [10]). When the crack propagates, the maximum number of units detaching simultaneously will determine the peak force that was needed to detach the whole pad. We call this peak value $F_{Release}$. Since the only energy this device consumes happens during the peeling phase how small $F_{Release}$ is an indicator of how efficient the device is.

Footprint effect. Fig. 6 illustrates the advantage of using a *triangularly* shaped footprint instead of a rectangular one. The smaller F_{Start} the *smoother* the release motion can be initiated. On the other end, when the propagating crack (wave) arrives to the pad's end it is desirable that it does so with low energy so the pad is not propelled to the void upon detachment (5h). Experimental data for the hand-pad: F_{Start}.=4.6 N; $F_{Release}$= *26N* . Summarizing, a way to make the release motion smoother (ie. decrease F_{Start}) is to decrease the adhesion power of each unit. A way to decrease $F_{Release}$ is to decrease the widest peeling line that peeling wave will have to overcome.

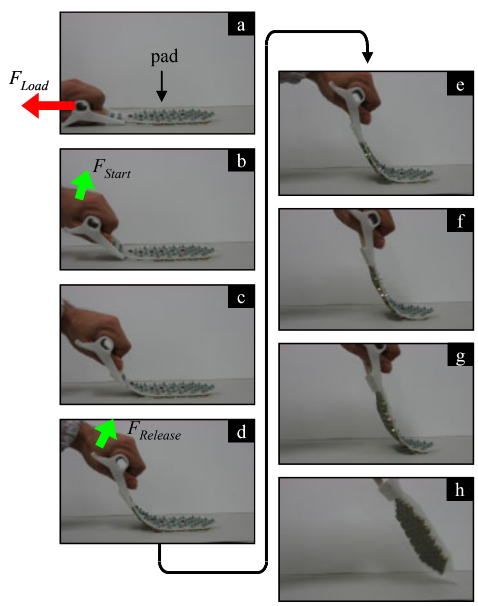


Fig. 5 Detachment by peeling motion. The minimum force necessary for detachment is 26 N while the load capacity is 500 N

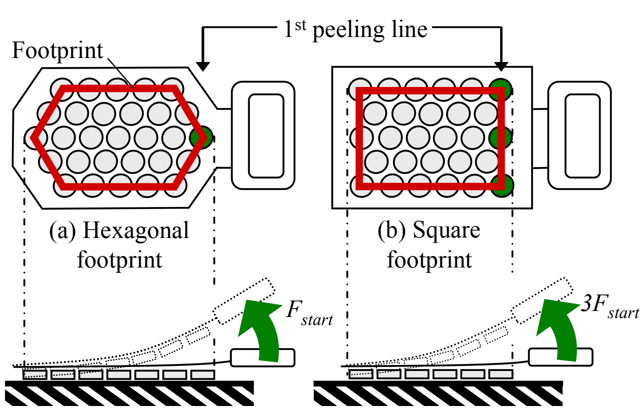


Fig. 6 Footprint effect. (a) Hexagonal footprint. (b) Square footprint. F_{Start} is the initial force necessary to start a pad-substrate peeling crack

C. Load Capacity & Performance

C-1. Theoretical Considerations

As we pointed out in section III, the load capacity is maximum in a direction tangential to the surface (as in geckos) and minimum in the direction normal to the surface. The maximum load a pad can support tangentially we call $F_{maxLoad}$. By inspection, for a pad system consisting of N adhesion units, $F_{maxLoad}$ can be expressed by as:

$$F_{maxLoad} \approx N \mu_s F_{Breakaway} \qquad (1)$$

where μ_s (the static friction coefficient) and $F_{Breakaway}$ refers to the adhesion units. Eq.1 is only valid if the load is distributed to all the adhesion units equally. This is, as in geckos, the role of the flexible support is not only to adapt to varying surface roughness (so all adhesion units are in close contact to the surface), but to *distribute* loads evenly in order to maximize the load capacity of the whole system.

C-2. Experimental Results

Fig. 7 shows the actual experiment of climbing a round wall by the device. The weight of the climbing man is 63kg.

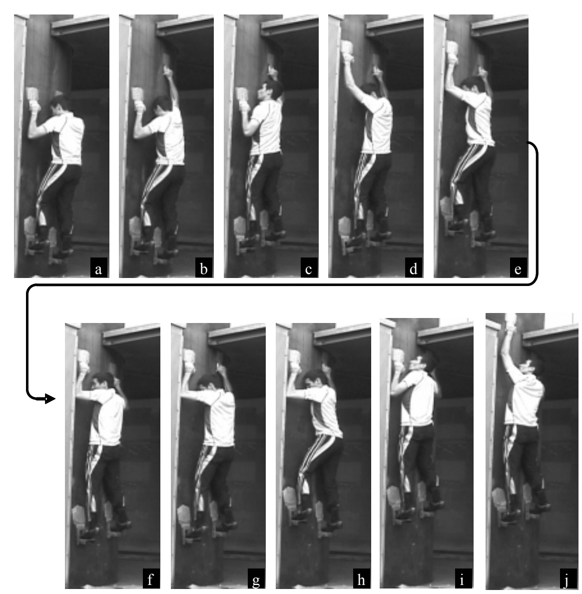


Fig. 7 A 63 Kg man climbing a round iron wall

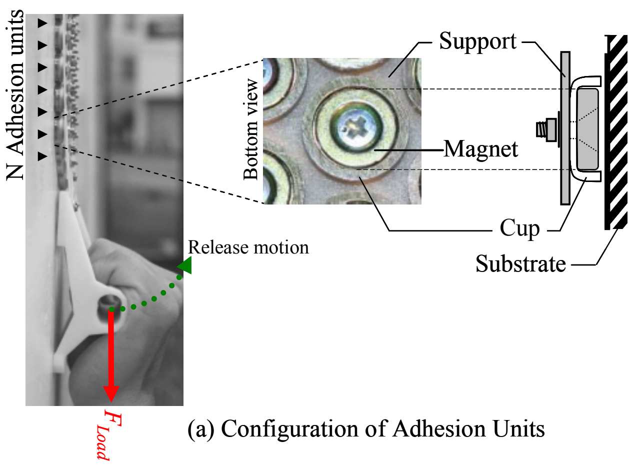
Fig. 8 shows a polar graph of the hand-pad prototype. θ is the direction of the load, $\rho(\theta)$ is the maximum supported load before an undesired detachment occurs (capacity). The value is normalized by $F_{Release}$ which is ρ for $\theta = 0$. Normalization, this is, comparing *Load Capacity* with how "easy" is a pad to detach is a measure of the *performance* or merit of a pad. Thus we define:

$$(\textit{Performance coefficient}) = F_{maxLoad} / F_{Release} \qquad (2)$$

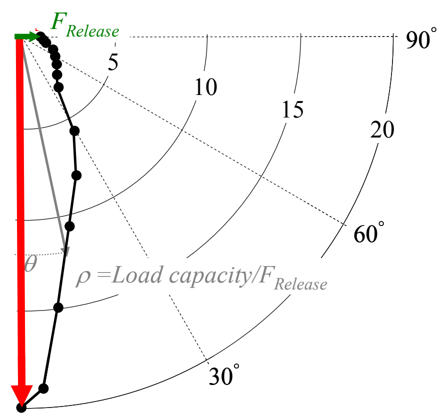
experimentally, $F_{Release}$ is proportional to the *width* of the widest peeling line (which is proportional to the *width* of the pad). On the other hand, if the aspect ratio of the pad is fixed then the $width \propto Area^{1/2}$. Since $Area \propto N$,

$$Performance = F_{maxLoad} / F_{Release} \propto N/N^{1/2} = N^{1/2} \qquad (3)$$

Eq.3 tells us that the *performance* of a pad will grow with $N^{1/2}$ and that is independent of the load capacity.



(a) Configuration of Adhesion Units



(b) Relation between Load Capacity and $F_{release}$

Fig. 8 Normalized *Load Capacity* vs. direction . The angle θ indicates the direction of the load force. $\rho(\theta)$ = Max Load(θ)/$F_{Release}$. $F_{Release}$ is the minimum force necessary to release the pad.

D. Surface roughness adaptability

In Fig. 9, pads adhere to the curved surface: a pole. The pad can adapt to cylinder-concave curvatures up to radius 50 mm and to convex curvatures up to radius 10 cm. This limitation is due to the minimum spacing between magnets, which are arranged in a closed packed pattern.

On roughness such as ones consisting of a protuberance, junctions and small steps, the loss of adhesion is noticeable. However, compared to previous comparable devices [5], a distributed system has the advantage that the loss of adhesion tends to be less critical. A protuberance or step in the middle of the pad might prevent effective contact of a considerable area of the pad (with the consequent proportional loss of adhesion), but in a non-compliant non-distributed system the loss tends to be more drastic. Because the adhesion is distributed the system is more robust.

E. Producing normal grip

E-1. Theoretical Considerations

As we have seen, a device based on pads has little ability to generate grip in a direction normal to the substrate (Fig. 8). This is fine in applications where loads are tangential (Fig. 9) but in factory automation the ability to produce normal grip is desirable since it simplifies operations (objects can be picked-up by simple contact form the top).

Fig. 9 Pole Climbing (a) A 58kg volunteer using **Magnetic Pads** to watch a game from a high vantage point. (b) Close-up. Adaptability to round surface: a pole.

Nevertheless, normal grip can be produced if we take advantage of the fact that an appreciable amount of normal adhesion (up to 15% of $F_{MaxLoad}$) exists when the load force forms a 30˚ angle with the substrate (Fig. 8). Figs. 10, 11 show how to pick up an object using a *pair configuration*.

E-2. Experimental Result

Based on Fig. 10 we can determine the normal load capacity ($F_{\perp Max}$) to be

$$F_{\perp max} = 2\rho(\theta_{max})\sin(\theta_{max}) \quad (4)$$

where ρ is the load capacity of a single pad and θ_{max} is the angle at which the normal component of the load capacity is maximum, (30˚ in the case of the pads we are considering). By design:

$$\rho(\theta_{max}) \propto F_{maxLoad} \propto N\mu_s F_{Breakaway} \quad (5)$$

Eq. 4, 5 tell us that to increase the normal grip we can either: a) increase N (which increases the contact area, making the device bigger), b) increase the tangential grip of each adhesion unit, or c) increase the term $\rho(\theta_{max})\sin(\theta_{max})$ with respect to $F_{maxLoad}$, this is, to increase $\sin(\theta_{max})\rho(\theta_{max})/\rho(0^\circ)$ (15% in the tested prototype). This value seems to be a structural characteristic of the pad design. Thus we conclude experimentally that the used pair pad configuration cannot produce normal grip larger than 15% of the combined maximum load capacity. This is equivalent to an adhesion pressure of 0.03 atm. (2mm iron plate)

F. *Automation of peeling motion*

Fig. 11 shows a simple device that automates peeling motion by a simple coupling mechanism. Fig. 12 shows a peeling wave sequence. The motor cannot detach 10 magnets by itself but it can detach them one by one. Peeling reduces peak power consumption allowing the use of light motors.Fig. 13 shows the device climbing a structural iron pipe.

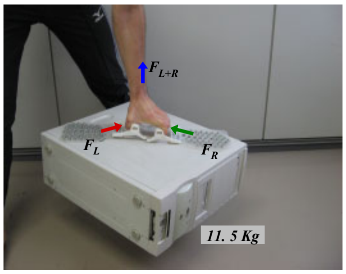


Fig. 9 Paired configuration used to lift a 11.5 Kg object. This configuration has a normal maximum grip capacity of 15Kg

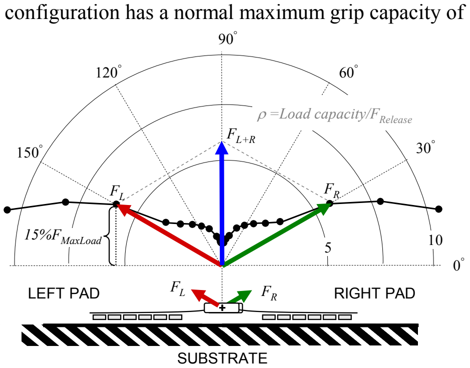


Fig. 10 Normal Grip. All forces are normalized by $F_{Release}$. Normal grip is produced by adding adhesion from the left pad (F_L) and right pad (F_R). Data of hand pads of fig 9. A pair configuration can produce a normal grip equivalent to 15% of the combined max (tangential) load capacity.

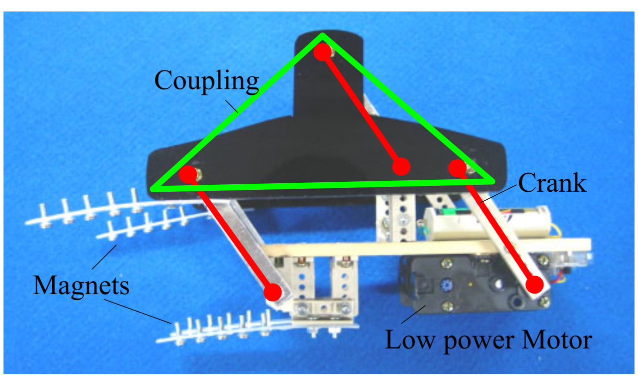


Fig. 11 Simple Automation of Peeling Motion. Sub-optimal peeling motion can be achieved by means of 6 cranks and 2 couplings.

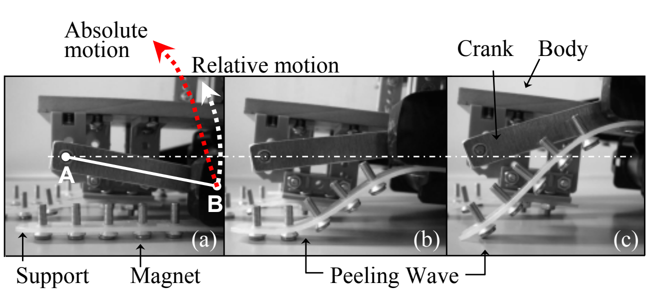


Fig. 12 Peeling Wave Sequence

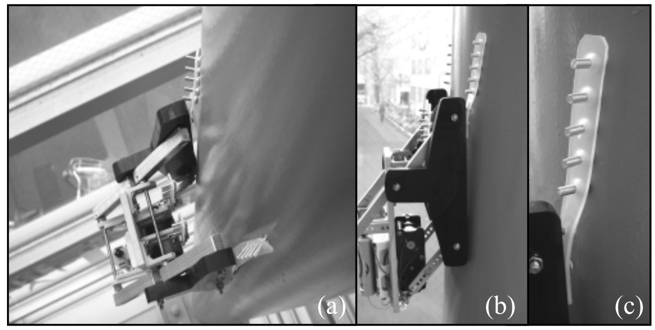


Fig. 13 A peeling based device climbing a structural pipe.

V. Conclusion & Future Works

We have introduced the concept of *distributed adhesion*. A magnetic pad implementation has been characterized. A vehicle that automates peeling-motion has been presented. We postulate that the *performance* of these devices depends only on the footprint profile and the number of adhesion units (N). The performance is then independent of the adhesion force used. We are developing an electrostatic version capable of climbing brick and mortar walls and non-ferromagnetic substrates.

Acknowledgment

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