2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

On the Form and Function of Gecko foot-hair for Wall Mobility (video background)

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I. INTORDUCTION

In this videopaper, we introduce a climbing system inspired by gecko foot that uses magnets instead of Van der Waals interaction to achieve controlled adhesion.

A. Van der Waals force for an object-on-plate system

It is known that gecko foot adhere to surfaces by means of Van der Waals force [1]. On the other hand, it is also generally accepted that very small bodies are subject to the so called Van der Waals interaction. An object of radius = *R*, separated from a flat surface by a distance = *d*, will experiment an attractive force. When the object is very close to the surface, $d \ll R$, the force is approximately proportional to d^{-1} (near field approximation). When *d* becomes comparable to *R* (we set a threshold at $d=R/20$) the force decreases with the 6^{th} or 7^{th} power of the distance [2]. Clearly this system is characterized by two markedly different behaviors. Which one dominates is decided by the d/R ratio.

B. Magnetic force for an object-on-plate system

On the other hand, if we suspend a cylindrical magnet over an iron plate, this "object" will experiment an attractive force towards the plate.

C. Comparison

Fig. 1 shows, simultaneously, the force-curves of both cases. X-axis is the normalized gap between an object and a plate. Y-axis represents the attractive force that the object experiments when suspended over a plate (or iron plate). The dots are experimental data for a magnet–iron plate system. The dashed arrows are the (theoretically predicted) Van der Waals force (VdW) [2]. (Qualitative trend only).

Behaviors in common:

1) Slow decay in "short-range" ($d \ll R$)
2) A steep decay the moment *d* becomes comparable to *R* ($d > R/20$)

Though the decay rates are different, let's note the sudden "switch" of behaviors present in both cases.

D. Force Substitution hypothesis

Since, the forces behave similarly; it should be possible to substitute one for the other in a real system. For example, if we substitute the Van der Waals force that acts on gecko's spatulae by magnetic force, the mechanical principles that allow geckos to walk graciously [3] and energy efficiently [4] should also work in our "magnetic" version of a gecko foot. Of course we should take into account scale factors, and that such a gecko would have to walk on a ferromagnetic substrate. We can build such a device by making a structure similar to a gecko foot and by attaching a magnet to each spatula (hair). The Van der Waals interaction becomes negligible by scaling the spatulas by a factor of 100 or bigger. We call this hypothesis force substitution hypothesis. The rest of the paper is based on the validity of this hypothesis.

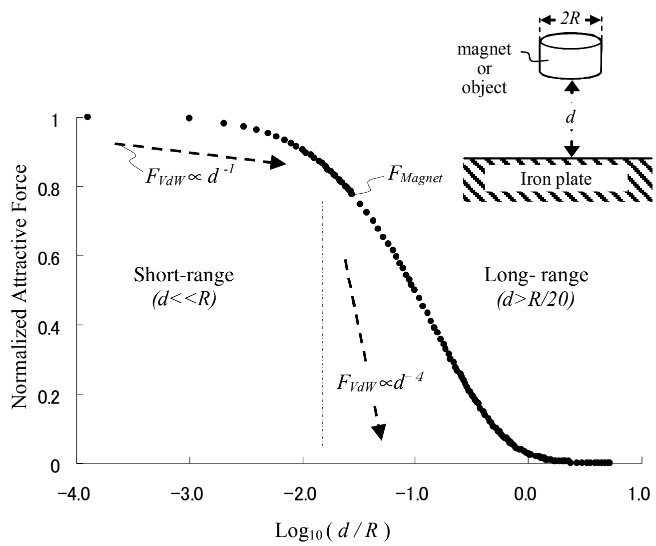

Fig. 1 Two forces with similar behaviors; *d* = plate-object gap. *R* = radius of object. Dots: measurement of attraction force between a cylindrical magnet and an iron plate. (Height of object ≤ R) Dashed arrows are the theoretical prediction of Van der Waals interaction. Qualitative trend only.

Fig. 1 dots correspond to a cylindrical rare earth magnet of 2 mm in diameter and 0.5 mm of height. The pull force has been normalized by the maximum force that acts on the magnet, (when $d \rightarrow 0$). This maximum force is also known as the *break away* force. The distance expressed in the X-axis is normalized by the radius of the magnet.

E. Magnetic Hair example

Based on D, Fig. 2 represents a model of a 5 finger magnetic hair pad, modeled after a gecko foot, where the function of Wan der Waals force has been substituted by magnetic force. Each spatula ends up in a cylindrical magnet. These spatulae are around 3 orders of magnitude bigger than the original ones.

However, the question remains, how good is the solution proposed in Fig. 2 compared to other systems?

II. Competing Climbing Mechanisms

Table 1 reviews competing systems for wall mobility.

TABLE I
COMPARISON OF FOUR WALL CLIMBING MECHANISMS

	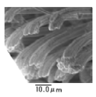	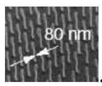	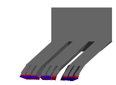	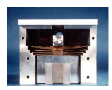
Device	Gecko foot	Artificial Gecko Hair	Magnetic Hair	IB Magnet[5]
Force type	Van der Waals	Van der Waals	Magnetic	Magnetic
Hair diameter	0.2 µm	80nm~0.2µm	0.2 mm ~ 1cm	Not apply
Production method	Live creature	Forming, lithography	3D printer	Handmade
Cost	-	High	Low	Low
Usability	Impractical [6]	?	Scalable	Difficult to miniaturize
Places where it can be used	Not suitable for oil-dirt environments [7]		Ferromagnetic structures only. Uneven, curved surfaces OK	Ferromagnetic structures. No curved surfaces
Performance coefficient	Very efficient [4]		1%~2% (Stable)	~ 5% But sensitive to steel grade, thickness

Table I pictures from left to right: 1. Gecko grossmanir spatulae. 2. Hitachi "nanopilar", (picture courtesy of Hitachi K.K.). 3. Illustration of Magnetic Hair. 4. IB Magnet (picture courtesy of Prof. Shigeo Hirose, Tokyo Institute of Technology). Product comparison matrix adapted from [8]

A. Performance coefficient: Detachment ease vs Maximum holding power

When a gecko walks on a vertical wall it does so in a very energy-efficient manner [4]. When a foot is attached to the wall it provides enough adhesion force that prevents the gecko of falling down. At the same time, when the gecko takes a step forward it can detach the foot from the wall almost effortlessly. Some descriptions of these phenomena can be found in the literature. However, when evaluating the merit of a climbing mechanism, it all boils down to a trade-off between

a. Maximum load (how much weight can it hold?)

vs

b. Ease of detachment (how much is the peak force needed to perform a successful detachment?)

If we define:

$$(Performance\ coefficient) = b / a \quad (1)$$

we can readily quantify the merit of similar systems. As shown in Table 1, a typical value of performance for an Internally Balanced Magnet is 5%. In the case of Magnetic Hair, provided each individual magnet is detached one at a time (see section III), the coefficient is proportional to the number of magnets that the system comprises. A typical value is 1~2%.

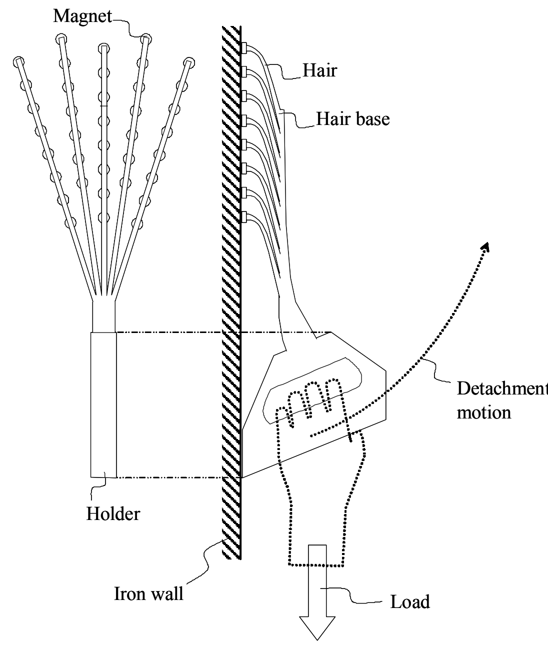

Fig. 2 Schema of a Magnetic Hair Pad.

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Abridged from *Magnetic Hair for Wall Mobility*, *Proc. of the IEEE IROS 2006*, Sept. 2006.