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Gecko Inspired Surface Climbing Robots

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Abstract— **Many applications call for robots to perform tasks in workspaces where traditional vehicles cannot reach. Using robots to perform these tasks can afford better human safety as well as lower cost operations. This paper focuses on the development of gecko inspired synthetic dry adhesives for wall climbing robots which can scale vertical walls. Many applications are of great interest for this kind of robot such as inspection, repair, cleaning, and exploration. The fabrication of synthetic dry adhesives inspired by nature is discussed as well as the design of prototype wall climbing robots. Results are presented and discussed to show the feasibility of novel Gecko inspired robots.**

Index Terms— **Biomimetic adhesives, biomimetic miniature robots, gecko adhesion, mobile robotics**

I. Introduction

A robot which can operate on a vertically oriented surface allows the possibility of automating tasks which are currently accomplished manually, affording an extra measure of human safety, often in a more cost effective manner. Some wall-climbing robots are in use in industry today cleaning high-rise buildings, and performing inspections in dangerous environments such as storage tanks for petroleum industries and nuclear power plants [1]. Recently, there has also been interest in using robots to inspect and repair space vehicles.

In literature, two main types of attachment mechanisms were studied and developed for wall climbing robots. The most common type is suction adhesion [2,3,4] where the robot carries an onboard pump to create a vacuum inside cups which are pressed against the wall or ceiling. This type of attachment has some major drawbacks associated with it. The suction adhesion mechanism requires time to develop enough vacuum to generate sufficient adhesion force. This delay may reduce the speed at which the robot can locomote. Another issue associated with suction adhesion is that any gap in the seal can cause the robot to fall. This drawback limits the suction cup adhesion mechanism to relatively smooth, non-porous, non-cracked surfaces. Lastly, the suction adhesion mechanism relies on the ambient pressure to stick to a wall, and therefore is not useful in space applications as the ambient pressure in space is essentially zero.

Another common type of adhesion mechanism is magnetic adhesion [5,6]. Magnetic adhesion has been implemented in wall climbing robots for specific applications such as nuclear facilities inspection. In specific cases where the surface allows, magnetic attachment can be highly desirable for its inherent reliability. Despite that, magnetic attachment is useful only in specific environments where the surface is ferromagnetic, so for most applications it is an unsuitable choice.

In this paper an unconventional attaching method is discussed. Inspired by climbing animals, new strategies can be developed for use in climbing robots. In fact, many animals have the desirable ability to stick to and climb on various surfaces. Insects, beetles, skinks, anoles, frogs and geckos have been studied for their sticking abilities. In particular, geckos are the most interesting because of their size. The Tokay gecko can weigh up to 300 grams and reach lengths of 35 cm yet is still able to run inverted and cling to smooth walls. By studying and imitating the attachment mechanism of this gecko, a new generation of robots can be developed making locomotion possible in almost any kind of surface without contaminating the environment.

II. Dry adhesion

For over 2 millennia, humans have watched lizards and bugs scale vertical surfaces in awe [7]. Only recently the attachment mechanisms of these animals have been understood. It is now possible to use similar mechanisms to allow robots to climb in the same manner as these animals.

Geckos' ability to climb surfaces, whether wet or dry, smooth or rough, has attracted scientists attention for decades. By means of compliant micro/nano-scale high aspect ratio beta-keratin structures at their feet, geckos manage to adhere to almost any surface with a controlled contact area [7]. It has been shown that adhesion is mainly due to molecular forces such as van der Waals forces [8].

The gecko's ability to stick to surfaces lies in its feet, specifically the very fine hairs on its toes. There are billions of these tiny fibers which make contact with the surface and create a significant collective surface area of contact. The hairs have physical properties which let them bend and conform to a wide variety of surface roughness, meaning that the adhesion arises from the structure of these hairs themselves.

The structure of the biological gecko foot-hair is very complicated and miniscule. Each fiber is made from multiple sections. Each fiber consist of a micro-hair (seta) which is roughly 5 microns in diameter, and atop each of these microfibers sit hundreds of nano-fibers (spatulae) which are 200 nanometers in diameter. There are between 100 and 1,000 spatulae on the end of each seta [9].

Although the surface area of each of the hair tips is very small, the combination of the area of billions of these hairs makes the effective surface area quite large, and surface forces (particularly van der Waals forces) become significant. Since the hairs are individually compliant, they can deform to match different surface roughnesses. Also, because of their hydrophobic nature, the gecko fibers are self-cleaning. In order for the dry adhesion to function, a small preload force normal to the surface is required to force the compliant hairs to configure themselves properly. Once this preload force has been applied, the material will stick until peeled off. The adhesion force can be as high as 10N per $1cm^2$ area [7].

Since dry adhesion is caused by van der Waals forces, surface chemistry is not of great importance [8]. This means that dry adhesion will work on almost any surface.

Much like the real gecko material, the synthetic adhesive will be super-hydrophobic and therefore be self-cleaning allowing for long lifetime robots. The nature of the adhesion force is such that no energy is required to maintain attachment after it has been initiated, so a robot using dry adhesion could hang on a wall indefinitely with no power consumption.

Another benefit of dry adhesion is the speed at which attachment and detachment is possible. The attachment is nearly instantaneous as is the detachment, they both only depend on the force applied. This allows for no delay in locomotion, thus very fast locomotion speeds. Furthermore, it is not necessary to time the attachment as critically as with the electromagnetic attachment, only a force is required, so the attachment is passive in nature, and therefore simple to control.

Dry adhesion is more robust than the suction adhesion mechanism, if the dry adhesion pad encounters a crack or gap, there will still be adhesion on the parts of the pad that have made contact. This behavior permits a robot using dry adhesion to climb on a wider variety of surfaces. Also, since dry adhesion does not rely heavily on the surface material or the atmosphere, it is suitable for use in the vacuum of space as well as inside liquid environments

III. SYNTHETIC HAIR FABRICATION

As a first step in the synthetic gecko fiber fabrication it is necessary to develop techniques to create the micro and nano-fibers independently. Once this is accomplished, it is possible to begin integrating the two types of fibers into a single process. The final structure will be a micro-fiber with nano-fibers branching out the end of the micro-fiber as seen in Figure 1.

In this paper, two methods to replicate the structure which use micro-molding techniques are described whereas the theoretical aspects are discussed in [9], [10]. The first fabrication method utilizes commercially available components while the second method utilizes MEMS techniques to fabricate custom master molds. In both methods, liquid polymer is poured over the molds and cured. The cured molded polymer emerges in the desired physical form. It is possible to approximate the physical characteristics of the beta keratin by selecting the proper polymer. In the first method a commercially purchased porous membrane is used as the mold. This membrane can have pore size of 0.02-20μm, thickness of 5μm, and pore density of 10^5-10^8 pores/cm^2. The larger sized diameter polycarbonate membranes have a random orientation of the nano-pores (±15°) created by a nuclear track etch while the smaller alumina membranes have very high density and directional uniformity. The thin porous membrane is attached to a substrate and is molded with polydimethyl siloxane (PDMS) or a similar polymer under vacuum. The vacuum is used to evacuate air from the pores so that the polymer can easily flow into them. After curing, the hardened polymer can either be mechanically peeled away from the membrane or the membrane can be chemically etched away.

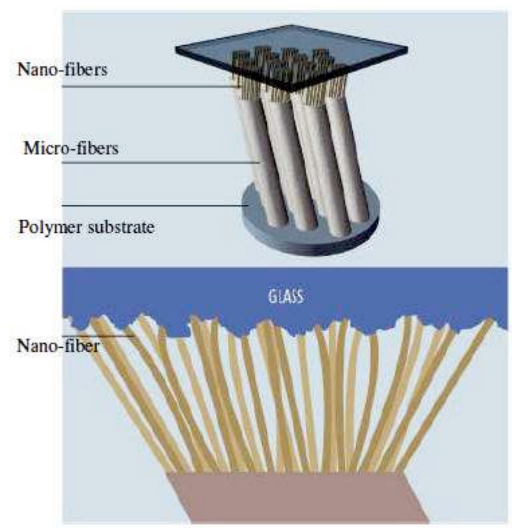


Figure 1 Micro and nano-scale gecko foot-fibers

Results from this method are promising. 200nm diameter high aspect ratio fibers have been produced Figure 2, which are similar to the distal hairs found in geckos. From this image it is clear that there is bunching or matting occurring between the fibers, likely due to the superfluous length of the fibers. As the length of the fibers increases, the inter-fiber adhesion force surpasses the spring force of the fiber to remain upright and the fibers begin to bunch. This problem is caused by the high aspect ratio of the commercially available nanopore membrane as well as the high density (fibers/area). To avoid this bunching issue, a second method of fabrication was developed in which the density, diameter and length could be independently controlled. This method entails patterning a silicon wafer through photolithography and using a deep reactive ion etch to create a negative mold for the fibers. As a last step in the etching process a thin conformal layer of fluorocarbon is deposited. This layer reduces the adhesion between the polymer and the mold which decreases the chances of the fibers breaking off and remaining in the mold during the peeling process, increasing yields. The same vacuum molding and heat curing process is used to create the fibers and the molded polymer is mechanically peeled off of the silicon. Micro-fiber results from this process can be seen in Figure 3.

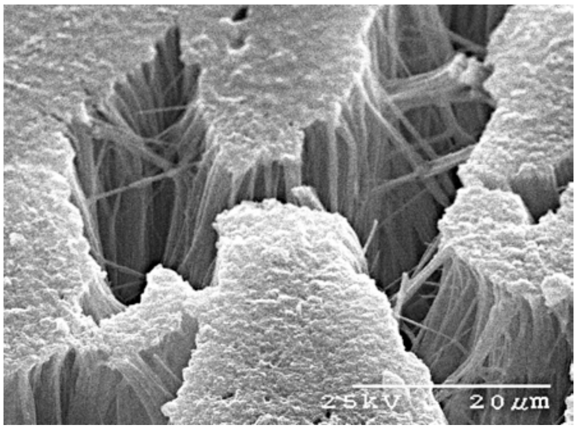


Figure 2 200nm diameter high aspect ratio polymer nano-fibers

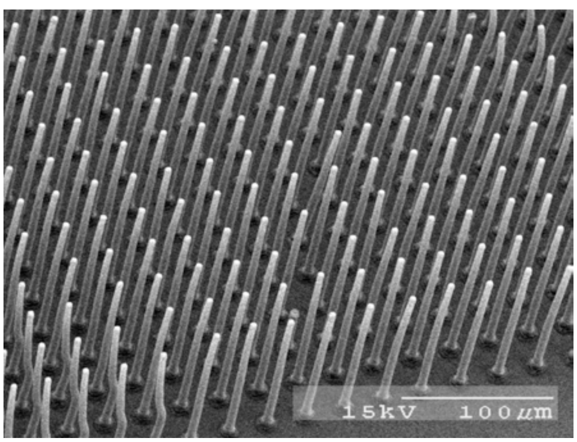


Figure 3 4µm diameter polymer micro-fibers

These 4µm diameter fibers show a very uniform structure, demonstrating the advantage of this new technique. Previous problems with fibers breaking off during the peeling phase seem to have been alleviated with the use of the fluorocarbon passivation layer, as it is rare to find any broken fibers.

IV. ROBOT DESIGN USING DRY ADHESIVES

A climbing robot design, using dry adhesion forces, has to be developed in order to maximize the effectiveness of the attachment system. In particular there are three main requirements for developing such a robot:

1. Maximize the attachment area.
2. Apply preload between vehicle and vertical surface for increasing the attaching force.
3. Use peel force during the detaching phase.

Two different vehicle concepts were developed. The first one is a wheg (wheel-leg) vehicle that uses legs with adhesive feet for climbing vertical surface. The second one is a tread-based locomotive mechanism using a rubber belt in place of a chain tire.

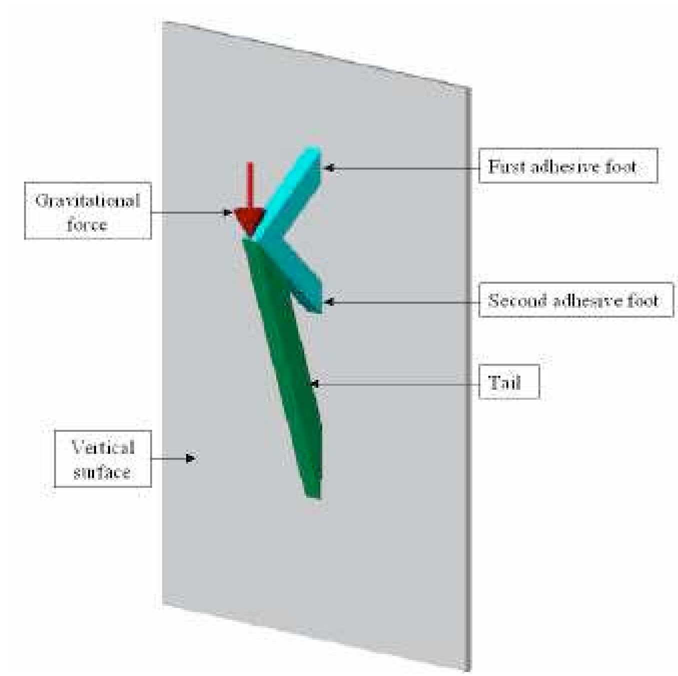


Figure 4 Schematic representation of whegs and tank climbing robots

Both the systems have a "tail" (Figure 4) whose purpose is to preload the robots against the vertical surface to be climbed.

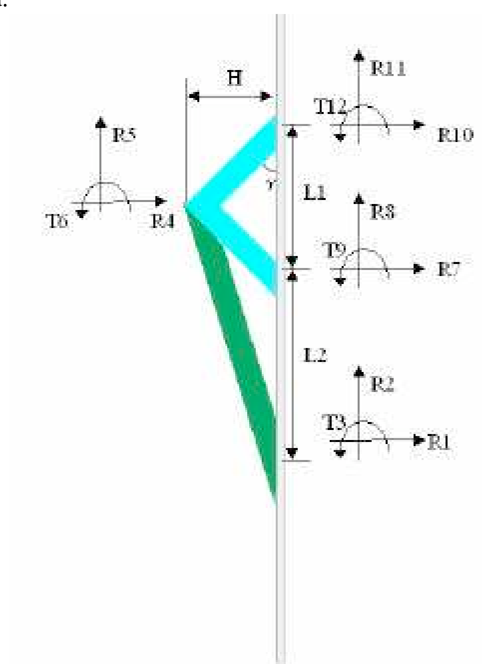


Figure 5 Forces and dimensions of the climbing robot model used on FEM optimization

In order to achieve good performances, an optimization analysis was performed. The properties of the tail and the position of the center of mass were optimized. Finite Element Methods (FEM) was chosen for solving and optimizing the over-constrained model shown in Figure 4. In the FEM model, the climbing robots were schematized by means of three beam elements having null masses. The gravitational force was applied in the center of mass of the system.

Figure 5 shows the directions of the forces that act on the system. The optimization focused on minimizing the force R10 since that corresponds to small attaching requirements for the employed adhesive. The results of the optimization, presented in Figures 6-8, correspond to a vehicle having the same dimensions of the developed tank robot. Specifications of the two prototypes are shown in Table 1.

Property	*Units*	*Tank*	*Whegs*
Voltage	V	2-6	2-6
Weight	kg	0.1	0.09
Length*	m	0.1	0.06
Width	m	0.07	0.08
Height	m	0.05	0.06
Tail length	m	0.09	0.09

**Without tail*

Table 1 Specifications of Tank and Wheg robots

Figure 6 shows how the force R10 varies changing the length and the rigidity of the tail of the model depictured in Figure 4. The attaching force has a monotone behavior with respect to the Young's modulus but there is a local minimum for the tail length. From these results, it can be summarized that the optimal tail length for the current configuration should be 0.12 meter long and the Young's modulus should be the highest possible.

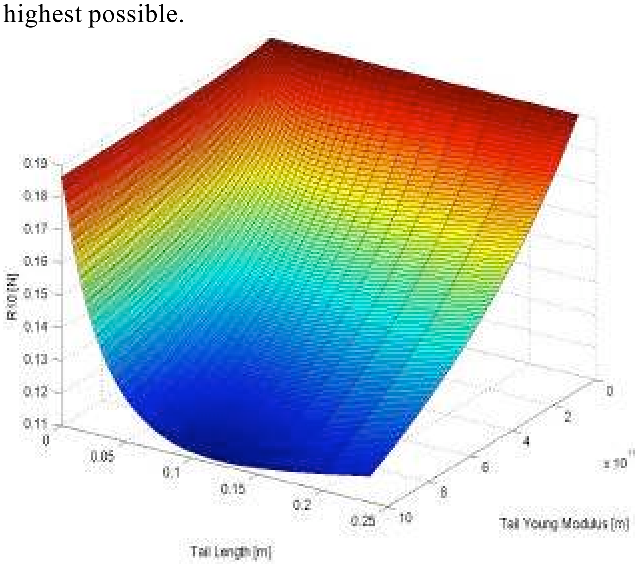


Figure 6 Adhesive force R10 required by a climbing robot as a function of tail length and stiffness

Figure 7 shows that for any considered values of the tail length and stiffness, the R7 force (Figure 5) is always negative. That means that the climbing robot exerts a positive pressure against the vertical surface providing the requested preloading force. The effect of the tail stiffness is dominant compared to the effect of tail length on force R7 as shown in Figure 7.

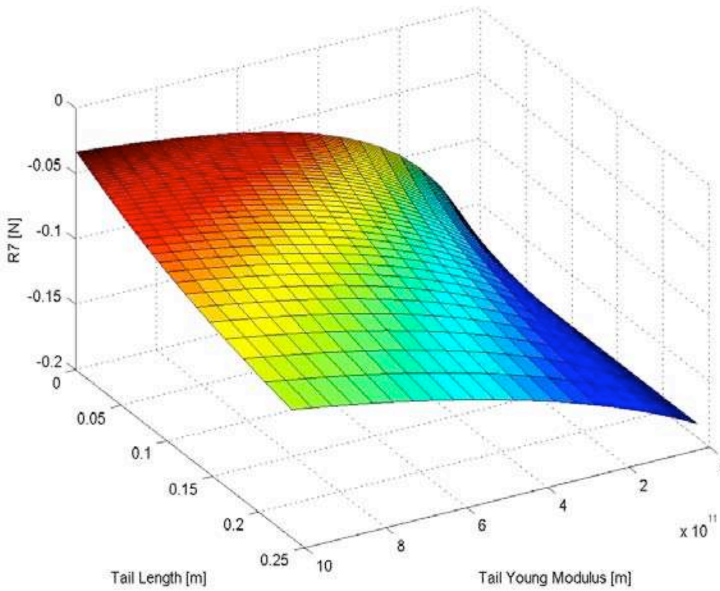


Figure 7 Contact force R7 required by a climbing robot as a function of tail length and stiffness

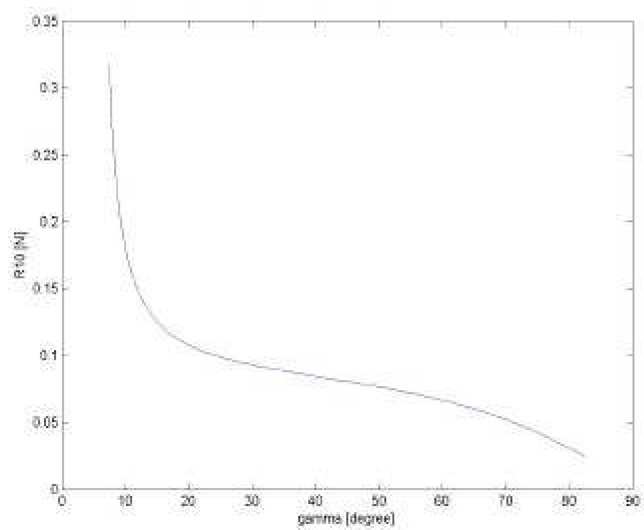


Figure 8 Adhesive force required by a climbing robot as a function of center of mass position

The position of the center of mass is also of great interest for a climbing vehicle. Taking into account the sketch depicted in Figure 5, the performed simulations were conducted changing the angle γ and keeping unchanged the variables H, L1 and L2. The results of Figure 8 point out that the center of mass should be positioned on the fore part of the vehicle for reducing the attaching force R10. Nevertheless, since from 20° to 70° the function does not present a steep slope, small changes in positions of the center of mass do not affect the performance of the vehicle.

V. Construction and Results

Two different vehicles were developed to show the feasibility of the climbing mechanisms. The first one, shown in Figure 9, uses legged wheels. This robot has 3 feet per wheg. Each foot had one degree of freedom through a passive revolute joint so that it is able to maintain contact with the surface throughout 120° of leg rotation. Conventional adhesive pads were placed on the bottom surface of these feet. To ensure that the feet were properly aligned as they approach the surface, elastic material was used as a spring to pull the feet back into the proper position after each detachment.

For proof of concept experiments, a double-sided foam adhesive was used to demonstrate the locomotion feasibility. The robot was able to climb a smooth acrylic surface in vertical and past vertical climbing angles.

The robot detached from the wall on occasion, however the problems seemed to be associated with the adhesive pads and robot construction rather than the robot design. In the current design both whegs rotate in phase on the same shaft. This allows for straight line motion only, which is very limiting. However, this design can be modified to allow for independent wheg rotation. If properly implemented, this could enable the robot to make turns and increase mobility.

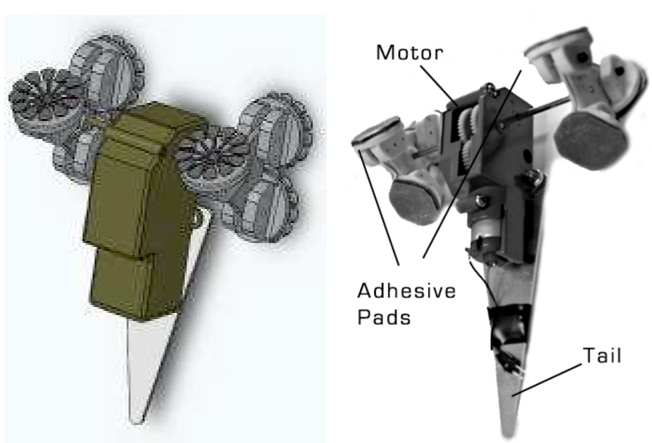


Figure 9 Robot with legged wheels: the CAD design (left image) and the photo of the real prototype (right image)

The second robot, depicted in Figure 10, consisted in a tread vehicle with customized tire. The chassis, pre-tensioning system and wheels were fabricated by means of a three dimensional prototyping machine. Different types of tires were built for testing the performance of the mechanism. In particular two were of great interest. The first type used very sticky foam that allowed the robot to climb vertical surface. The vehicle was also able to ride surfaces inclined at about 110° with respect to the horizontal ground plane. Since the robot are intended to utilize the synthetic dry adhesive as attachment mechanism, customized tire were designed and molded using PDMS, the same material that was chosen for the synthetic hair fabrication. For the sake of simplicity, the treads tires were built without hairs since the feasibility of the vehicle was the first goal to achieve.

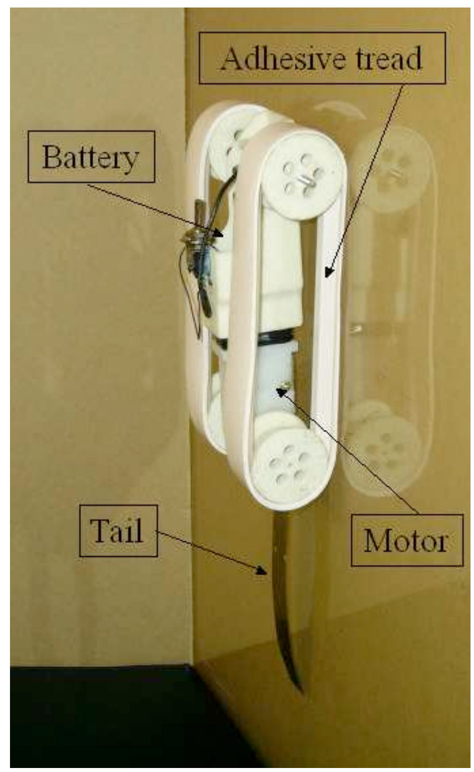
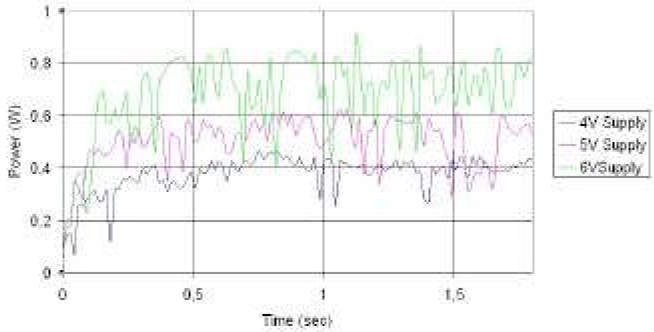
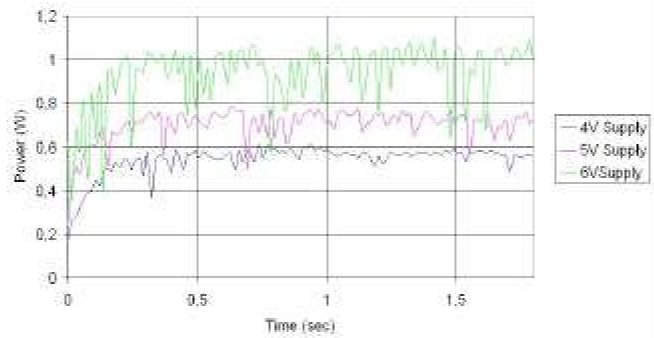


Figure 10 Photo of the tread-based locomotion mechanism

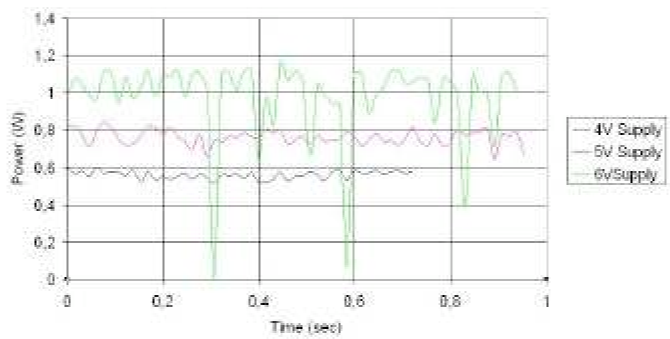
The wireless vehicle, equipped with PDMS treads, was able to climb an acrylic surface sloped at 75° showing a very reliable behavior. In Figure 11, the temporal evolution of the power consumption of the robot is depicted for several sloped surface and voltage inputs. At maximum speed, corresponding to an input of 6V, the vehicle consumed 1.1 W on average. Comparing the three different above figures, the power consumption of the climbing robot increases when the slope of the inclined surface is increased.



(a)



(b)



(c)

Figure 11 Temporal evolution of power consumption of the tread-robot moving on: (a) 0°, (b) 40°, (c) 75° sloped surfaces

In addition, the power measurements show microscopic stick-slip behavior that was not noticed with visual macroscopic inspection. In fact, for high voltage input, Figure 11c presents lower peaks respects to the other two figures. This behavior is associated to stick-slip phenomena that are more significant when the elastic belts of the tread-robot are mostly stretched. One possible solution for this issue is to increase the stiffness of the tires.

Equipping the tread-vehicle with synthetic hair would greatly increase the performance of the robot making it capable of climbing many types of surfaces for any slope angle without contaminating the surrounding environment.

VI. CONCLUSION

The importance of realizing mechanisms able to climb every kind of surface without contaminating the surrounding environment has driven the research to focus on the ability of animals to climb vertical walls.

In this paper, a new climb ing robot strategy was presented. Also a new technique for fabricating synthetic microfibers for use as dry adhesives and the results of this process were presented. Two robotic prototypes, equipped with conventional adhesives, were built, analyzed, and successfully tested. The prototypes were able to climb vertical smooth surfaces, demonstrating the feasibility of the novel robot designs. Future work includes improving the synthetic hair fabrication and the implementation of this material in more agile and robust climbing robots.

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