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Space exploration - towards bio-inspired climbing robots

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1. Introduction

Robotic systems continue to be an important tool in space exploration, and as robotic systems continue to gain capability, the particular challenges of the space environment and the tasks required in space will benefit from such systems finding new roles in space.
This chapter focuses on the design of climbing robots suitable for use in space. These mimic the climbing ability of geckos, using micro-structured hairs to provide dry adhesion, and exploit gait to exhibit rapid and robust motion over vertical surfaces on earth. Mobility of robotic systems allows many different roles for systems in space, including exploration on extraterrestrial surfaces and navigating vehicle surfaces in orbit.
Climbing robots in space may provide extra capability in the ability to negotiate a broader range of terrains. The range of surfaces that might be required to be negotiated in space can be matched by the range of different possible climbing strategies.
In particular, dry adhesive techniques inspired by the gecko are highlighted, with different robot designs intended to take advantage of such dry adhesives described in detail. Examples of other strategies for climbing robots are presented and discussed, particularly in the context of usefulness for future implementation in space.
With this section introducing the subject and composition of this chapter, section 2 gives a brief overview of the main challenges facing robotic systems in space. Section 3 is devoted to the introduction of different strategies for climbing robots, including examples designed for use in space. Examples of robotic systems employing different approaches are given. In section 4, the subject of biologically inspired synthetic dry adhesion is introduced. Section 5 forms the major part of this chapter, describing the design and breadboarding of three climbing robots, intended to form the basis for future robots using such dry adhesives. Future work is discussed in section 6 and conclusions are given in section 7.

2. Issues for Space Robotics

Robotic systems used in space are subject to a range of challenging environments from launch to deployment and operation, which must all be mitigated with great robustness given the impossibility of repair of most space-borne systems.

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The launch phase presents mechanical challenges to the system in terms of both static and dynamic loads. Mechanical interface of the robot to the connected part of the space vehicle must be considered in addition to the robotic system itself. These include high steady state acceleration, and significant low frequency longitudinal and lateral vibrations. Random vibrations caused by the engine, and thin layer noise are also present. Furthermore, in multi-stage launchers shocks are undergone when stage separations occur. Thermal conditions must be accounted for in the phases before launch, where the system must be prepared and integrated and then transferred to the launch site, as well as thermal conditions during launch. Mechanisms must also adhere to cleanliness requirements for launch, not only to avoid contaminants that may detriment systems on the robot or launcher, but in some cases also to avoid contamination of extraterrestrial environments that may interfere with scientific payload.

On orbit, the robotic system must mitigate the vacuum environment if not used inside a pressured spacecraft. Outgassing from materials in the robotic system must then be taken into account. In the case of earth orbit, the radiation environment will impact robotic design, for instance requiring the use of radiation hardened electronic components. Atomic oxygen, particularly abundant in low earth orbit, causes material dependent corrosion of surfaces. Since abundance of atomic oxygen in orbit is also dependent on solar flux, both solar activity and the eclipse cycling of the orbiting system will impact on this effect. Plasma effects are also orbit dependent, where at low altitude (100 – 1000 km) it is relatively cool, dense and regular, while at geosychronous altitude (35000 km) it is hot, irregular and highly variable. Collective effects dominate at low altitudes, where surface charging by plasma can cause, for instance, higher impedance in antennas. At geosychronous altitude, where effects of individual highly energetic plasma particles dominate, build-up of charge in components and subsequent discharging can cause critical failures in spacecraft. Space debris is an increasing problem around the earth. Smaller particles (10^{-3} – 10^{-9} g) cause erosion of surfaces, while mitigation of larger particles may require use of appropriate shielding materials. Finally, solar flux combined with periods of eclipse, mean that orbiting systems experience large changes in thermal environment. For subsystems, this is highly dependent on the system's orientation to the sun and the thermal design of the system. In general, thermal environment will also be highly dependent on orbit, with low altitude entailing a higher rate of thermal cycling due to a higher rate of eclipse cycles.

Extraterrestrial surface environments are varied, but may in addition to the above include factors such as large amounts of dust, extreme temperatures and pressures, and strong winds. Furthermore, deployment on a surface may entail more demanding mechanical loads dependent on landing characteristics.

In addition to the demands placed on robotic systems materials and structure, the remote nature of space environments demands robust operation in situations far from the reach or control of humans. Not only must the physical design of robotic space systems be in accordance with these demands, but various degrees of autonomy and intelligence is required from such systems. Furthermore, space systems are generally required to be energy efficient, and low in volume and mass.

Robotic systems continue to be of use in space in complementing human presence in space. While human agents in space provide adaptability in function presently unavailable to robots, the greatly reduced cost and risk involved in the use of robotic space systems means that they will continue to find uses in space for the foreseeable future. Indeed, as the capability of robotic systems increases, as does their potential for miniaturisation, new opportunities arise in enabling novel uses for robots in space.

3. Strategies for Climbing Robots

3.1 Negative pressure

Various robotic climbing systems have been based on suction adhesion. Generally, in comparison to other clinging mechanisms, generation of suction requires high power, and gaps in the seals in suction cups will negate the suction effect although some systems using dynamic suction have also been designed. In any case, since suction adhesion is reliant on ambient pressure, such systems are unsuitable for use in orbit.

Two robots, termed Flipper and Crawler, are examples of climbing robots that employ suction adhesion (Tummala *et. al.*, 2004). Intended for use as remote sensors in hostile terrestrial environments, they are capable of traversing both horizontal and inclined surfaces, as well as transiting between some surfaces with differing gradients. Their designs emphasise low power consumption, small size, and low weight.

While prototypes of these designs performed satisfactorily, speed was limited by the time taken to establish adhesion and release with the suction mechanism. Additionally, the systems were limited in the range of surfaces they could climb.

Another example, named Gecko (Cepolina *et. al.*, 2003), employs a novel suspension system to assure modulated pressure in its suction mechanisms. This is just one example of many robotic systems that have been designed for the cleaning of vertical terrestrial surfaces.

Dynamic suction has been implemented in commercially available robots, able to be used with a variety of payloads (Illingworth & Reinfeld, 2001). These systems are able to transition easily from horizontal to vertical surfaces using a 'tornado in a cup' vortex to generate suction. However, for adhesion to walls the dynamic vortex must be active even when stationary, requiring significant power expenditure.

3.2 Mechanical Grip

Like the dry adhesion employed by animals such as the gecko, many examples may be found in nature of species that employ mechanical grip in climbing. However, the use of mechanical grip for climbing is dependent on suitable surfaces, where for instance the climbing of a smooth inverted surface on earth using only mechanical grip would be unfeasible.

LEMUR IIb is a multi-limbed robot capable of free climbing near vertical surfaces (Bretl *et. al.*, 2004). Irregularities in an otherwise smooth surface are used to provide reaction force to the climbing limbs.

Eurobot is a robot designed for use in space that, in addition, utilises anthropomorphic manipulators at the ends of its limbs (Visentin, 2005; Joudrier *et. al.*, 2005). Under normal gravity conditions, such manipulators would allow extra grip when climbing inclined surfaces and enable robotic designs to cling to inverted surfaces, where handholds are available. Since Eurobot is primarily designed for use in microgravity, manipulators are required to remain attached to the spacecraft and can also be employed to perform tasks that would otherwise require and EVA astronaut.

Micro-spine clinging is another bioinspired climbing system, used in nature by various insects, arthropods and some species of gecko. Micro-scale spines take advantage of asperities (bumps or pits) on surfaces and provide reaction force to enable climbing of

vertical surfaces. Such systems allow clinging to porous or dusty surfaces and are not as susceptible to degrading from dust unlike currently manufactured, smaller scale gecko-inspired adhesive fibre arrays.
However, the micro-spine method is still surface dependent, although the technique is scalable to surfaces of differing roughness Such systems have been implemented on the Spinybot II and RiSE robots (Kim *et. al.,* 2005; Haynes & Rizzi, 2006).

3.3 Magnetic

Magnetic systems for climbing have also been designed, though clearly in this case a ferromagnetic surface is required to allow adhesion. In addition, for some space applications large magnetic forces might interfere with payload or other mission systems.
The hexapod REST robot (Grieco *et. al.*, 1998), uses a combination of permanent magnets and electromagnets to carry payloads of up to 100 kg while clinging to vertical or inverted surfaces. Safety is enhanced through the use of permanent magnets that retain adhesion in the case of a loss of power. Electromagnets reinforce grip during locomotion. Clearly this system is only suitable for climbing where ferromagnetic surfaces are available, and is therefore aimed at use only in terrestrial industrial environments. As neither planetary and satellite surfaces are usually ferromagnetic, this technique is not the most appropriate for space applications.

3.4 Dry Adhesive

In comparison to magnetic and suction approaches to adhesion, dry adhesion is passive and might therefore be thought of as having potential for the design of energy efficient systems, a compelling advantage in space applications. While it has been found that capillary forces may play a significant role in gecko-type adhesion, it has also been found that adhesion is still possible even in the absence of water, and that adhesion can still be produced in vacuum. Potentially, this type of adhesion would therefore be suitable for use in extraterrestrial environments as well as microgravity and vacuum environments.
Using Scotch® tape as an adhesive the Mini-Whegs™ robot uses wheel-legs for locomotion (Daltorio *et. al.*, 2005a). Each wheel foot consists of a rotating hub, with several compliant adhesive feet attached around its circumference. In this configuration, the robot was able to traverse vertical surfaces with relative ease and had some success in locomotion across inverted surfaces. The robot was found to be suitable for transitioning between surfaces of different inclination. The system has also been tested with microstructured polymer adhesives, achieving somewhat lower performance (Daltorio *et. al.*, 2005b).
Tri-Leg Waalbot, named after the Van der Waal's Forces it uses for adhesion, also uses wheel-legs for climbing smooth surfaces (Murphy *et. al.*, 2007). Its two legs hold six adhesive footpads which allow the robot to climb, transition, and turn in small corridors. Recent progress includes inverted walking and turning and integration of microstructured polymer adhesives into the footpads.
Extracting further attributes from gecko adhesion strategy, the Stickybot robot employs hierarchical compliance to increase contact area with the surface (Kim *et. al.*, 2007). The robot's construction implements compliance at micrometer, millimetre and centimetre scales to allow adhesion over a great portion of the robot surface, to surfaces that are uneven over these scales. Furthermore, directional adhesives and distributed force control are employed to increase performance. Polyurethane or Sorbothane® adhesives were used on early versions.

Foot design is crucial to the qualities displayed by gecko motion, such as robustness, and speed. Gecko footpads can adhere quickly, simply through approaching a surface, and then preloading against it and performing a dragging motion to maximise contact area with the surface, with gecko foot mechanical design enabling swift execution of such a dynamic. The mechanics of gecko feet also allow swift detachment from a surface, using a peeling motion to minimise the forces needed to overcome adhesion force.
Gait is another important factor in designing such robots and control of gait is a popular method for enabling stable locomotion in legged robots. In the particular case of climbing robots, control of force distribution over adhesive contact area is important to system performance and choice of gait has been used to enable this in systems utilising dry adhesives (Haynes & Rizzi, 2006). Increased structural compliance can be seen in various emerging research in climbing robots, including one of the designs described in section 5. In addition to enhancing other performance factors such as adhesion efficiency, purposeful compliance has been found to play an important role in running gaits of animals, impacting on the speed, efficiency and agility of locomotion (Hurst & Rizzi, 2004).

4. Dry Adhesion

4.1 Dry Adhesion in Nature

Several animal orders display the ability to adhere to a wide variety of surfaces without the use of mechanical grip and that leave no residue on the surface after detachment. Small-scale structures arranged in arrays on their feet are employed to cling robustly to surfaces.
These small-scale structures generally take the form of hairs either with arrays of simple angled cylindrical structure as with spiders and anoles, or including more complex branching fibres as in the case of the geckos (Figure 1). When attached to a surface, these arrays of hairs have analogous adhesive properties to an array of Velcro adhesive, in that, qualitatively, such arrays exert strong adhesive force in reaction to shear and strain forces, while allowing detachment with relatively little force in response to a peeling motion.

Figure 1. A gecko climbing smooth glass

Ongoing research shows that these hair-like structures impart adhesive forces through van der Waals forces formed between the hairs and the surface, as well as capillary forces in the presence of water (Huber *et. al.*, 2005, Sun *et. al.*, 2005). The inherent compliance of these hairs allows the contact area between them and a surface to be maximised under preloading. In addition, their material properties allow them to return to their original shape when not in contact with a surface.

As well as providing adhesion, setae in geckos have been shown to be self-cleaning, such that geckos with dirty footpads have been found to regain their climbing abilities within a few steps. This ability has been found to be retained by the setae in isolation from the gecko. It has been theorised that this ability stems from the nanoscale structure of the hairs themselves, and should therefore be reproducible in synthetically produced materials (Hansen & Autumn, 2005).

4.2 Synthetic Dry Adhesion Strategies

Since forces involved in gecko-like dry adhesion have been found to be dependent on the microstructured properties of hairs, rather than the hair material itself, many materials and fabrication techniques may be considered in the synthesis of analogous artificial dry adhesives. Various polymers (Sitti & Fearing, 2003), polymer organorods (Northern *et. al*., 2005), and multiwalled carbon nanotubes (Zhao *et. al.*, 2006) have been considered in conjunction with fabrication techniques such as electron-beam lithography (Geim *et. al*., 2003), micro/nano moulding (Glassmaker *et. al*., 2004; Majidi *et. al*., 2004; Sitti & Fearing, 2003) and self-assembly.

Various models for microfibre adhesion can be found in literature (Aksak *et. al*., 2007). While a basic approach to the manufacture of synthetic small-scale adhesive microfibre arrays might be to simply produce an array of simple cylindrical rods, it has been found that contact shape plays an important role in adhesion (Spoelnak *et. al*., 2005), and some work has addressed the design of mictrofibres with variable contact shape (Kim & Sitti, 2006; Shah & Sitti, 2004). The effect of use of angled fibres has also been modelled, and corresponding microfibre arrays manufactured (Aksak *et. al*., 2007)

Synthetic dry adhesives also attract dirt particles, and are not yet self-cleaning though current research theorises that self-cleaning ability in gecko setae is enabled by their nano-scale structure, and should therefore be able to be reproduced synthetically (Hansen & Autumn, 2005). Furthermore, gecko adhesive pads are self-repairing, a quality that is also lacking in synthetic analogues so far.

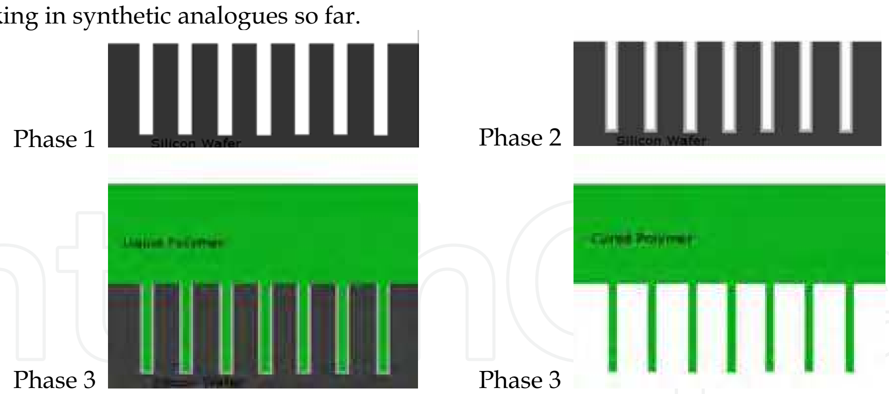

Figure 2. A polymeric micro-hair manufacture procedure

Different groups are investigating techniques to replicate the gecko adhesive with synthetic materials. In order to design and build an engineered bio-inspired dry adhesive, it is crucial to be able to reproduce gecko hairs in both their micro- and nano-structure. The following procedure (Menon *et. al.*, 2004) can be followed to build polymeric micro-hairs (see Figure 2): 1) a silicon wafer is prepared, using Deep Reactive Ion Etching (DRIE) technology, in order

to be a mould for the following phase; 2) a fluoro-carbon layer is then deposited - this facilitates the following demoulding phase; 3) a liquid polymer is poured on the silicon mould and is then thermally cured in a vacuum chamber to avoid the formation of undesired gas bubbles; 4) the cured polymer is mechanically peeled out of the mould - this phase is still very critical as micro-hairs could be torn.
Figure 3 shows an array of micro-hair fabricated by the authors following the procedure mentioned above. The material that was used for this particular application was polyurethane. The selection of the material is critical - it should be flexible enough to be compliant with the roughness of the surface, yet strong enough to withstand the lateral surface adhesion force exerted by the neighboring artificial hairs. The diameter of the gecko inspired hair shown in Figure 3 is approximately 2 μm.

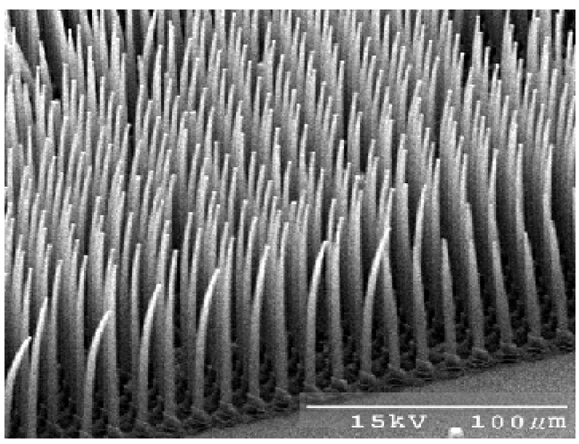

Figure 3. 2 μm diameter Polyurethane Fibres

5. Gecko Robot Designs

5.1 Tank robot

Different robotic prototypes suitable for using gecko inspired adhesive have been designed, developed and tested. A particularly suitable system is the tank robot (see Figure 4).
This robot, developed in 2004 by the authors (Menon at al., 2004), was able to climb vertical surfaces. The inherent advantage of this design is that the system naturally preloads the adhesive embedded into the wheel belt, making the artificial hair comply to the surface roughness. It then naturally detaches the adhesive, enabling efficient locomotion. The appendage on the back of the robot is used to preload the adhesive in the fore part of the robot. The prototype shown in Figure 4 has been built using rapid prototype fabrication technology. Its belts were produced in PDMS through a moulding process. This robot does not have artificial hair integrated on its wheel belts - this could however be accomplished by attaching synthetic adhesive patches to the belts or directly moulding wheel belts with micro-hairs embedded (PDMS is a suitable material to be used for the synthetic adhesive).
Besides the tank robot, an additional locomotion system that is particularly suitable for climbing vertical surfaces and upside down is the Tri-leg Waalbot robot, which is represented on the upper part of Figure 5. Three legs are attached to the motor shaft through revolute joints. An elastic spring is used to place the leg in the correct position for adhere to

the surface. This locomotion system is capable of preloading the legs by taking advantage of the force needed to detach the legs in contact with the surface. In Figure 5 the first wireless Tri-leg and tank prototypes built by the authors are compared.

Figure 4. Tank robot prototype

Figure 5. Tank (bottom) and Tri-Leg (top) robots

5.2 Two Gecko-Inspired Climbing Robots

Several gecko inspired robotic concepts have been designed and tested – here two promising prototypes are presented (Menon & Sitti, 2006). One of these designs has focused on the production of a robust and reliable system. Termed the Rigid Gecko Robot (RGR), this system is aimed at the design of macro scale systems. On the other hand, the shape memory alloy actuated Compliant Gecko Robot (CGR) has been designed to be suitable for miniaturisation. Both systems have been developed with the intention that similar systems may eventually take advantage of micro-structured arrays of dry adhesives.

5.3 Experimental Adhesion Design

While materials that mimic the structure of gecko adhesive pads have been realised synthetically, the experimental approach employed in the design of the following two robotic concepts required the use of commercially available materials suitable for use in extensive testing.

To test robotic designs that could eventually take advantage of synthetic gecko adhesive, materials were sought that would cause adhesion through use of climbing strategies that would be used for the synthetic gecko adhesive. As described above, arrays of gecko hairs are made to adhere to surfaces through the use of approach, preloading, and peeling phases of motion.

Two commercially available materials were considered for use in a system using these phases of motion to move their attaching parts, Silly Putty and polydimethyl siloxane (PDMS). As with arrays of gecko hairs, when such material is preloaded against a surface, their contact area is progressively maximised due to the material compliance, allowing many intramolecular bonds between adhesive and surface to be formed.

A customised measurement test-bed was used to test these two materials. Amounts of adhesive of with surface contact area of 95 mm^2 were preloaded against a glass surface. Initial preloading of 75 mN was employed, although due to the plastic deformation of the adhesives under pressure, this force decreases slightly after the initial contact. The materials deform in such a way as to fill hollows in surface roughness, thereby increasing contact area with the surface. Approach and retraction velocities employed were 0.08 ms^{-1} and 0.4 m s^{-1} respectively. Normal adhesive forces under the conditions described were compared for the two adhesives. Silly Putty was chosen for use in these robot designs due to the higher normal adhesive force displayed.

5.4 Foot Design

An idealised view of gecko foot dynamics is shown in Figure 6. Adhesion between footpad hairs and the surface is achieved as the footpads are preloaded and dragged against the surface, allowing the hairs to conform to the surface and maximise contact area. Subsequently, a twisting motion of the foot from the tip is used in the peeling phase to free the adhesive from the surface, where the pad separates from the surface after a critical angle of about 30 degrees.

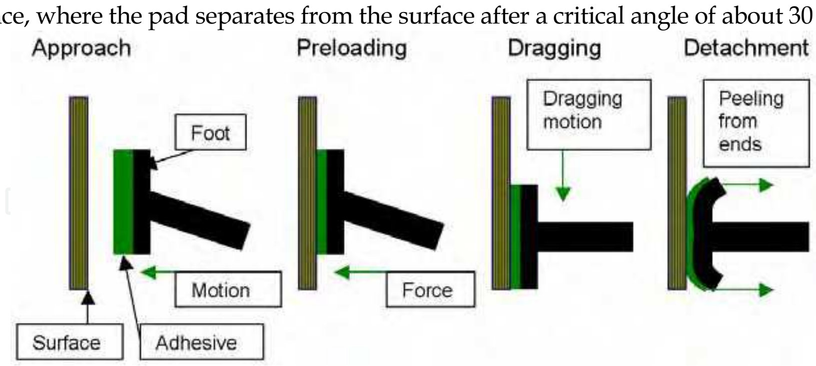

Figure 6. Idealised motion of a compliant robotic foot

For these experimental designs, the Silly Putty adhesive does not need to go through the dragging part of the motion to instigate adhesion. Preloading and peeling phases are implemented using the mechanism illustrated in Figure 7, consisting of a DC motor, rigid leg and compliant foot material to which the adhesive is attached.

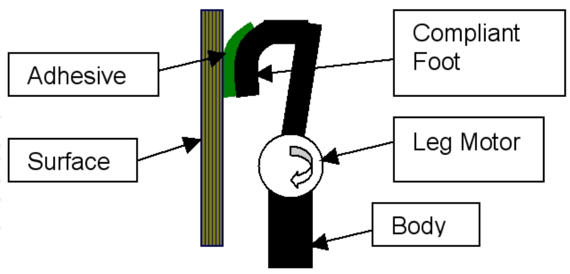

Figure 7. Foot Mechanism Design

5.5 RGR Design

A prototype was constructed as shown in Figure 8. Leg actuation is achieved through the labelled motorised leg joints. Another motorised joint is placed in the robot back, where actuation is required for locomotion in the middle of what is referred to as the robot's back. The remaining 5 degrees of freedom are passive revolute joints.

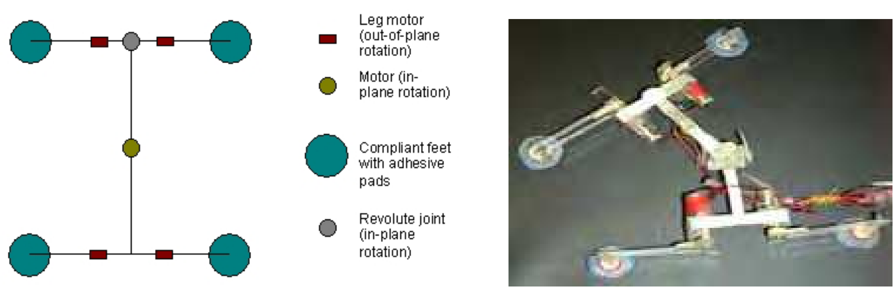

Figure 8. RGR design

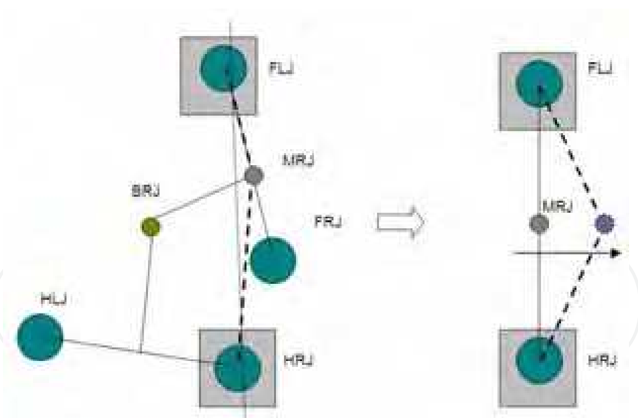

Figure 9. The RGR is represented in its unstable configuration the left; on the right is a schematic representation of the gecko robot, showing the model to be studied for the understanding of its unstable configuration. (FLJ=Fore Left Joint; HRJ=Hind Right Joint; FRJ=Fore Right Joint; HLJ=Hind Right Joint; BRJ=Back Right Joint; MRJ=Middle Revolute Joint.)

A combination of dynamic simulation and experimental data from a realistically specified 3 dimensional physical model was used to investigate the dynamics of the design. Dynamic modelling was carried out using multi-body simulations. Both physical and simulated models were 0.1 m long, 0.1 m wide and weighed 80 g. Torque of the back motor counterbalances the robot's weight and dynamic forces caused by it's motion. The total force acting on this foot was found to be 1.5N.

Since the chosen adhesive, Silly Putty, exhibits plastic behaviour, the Bowden Taybor equation may be used to determine the required contact area of the robot footpads, in conjunction with the multi-body simulation. This was found to be 6 cm^2.

Dynamic simulation showed numerical instabilities for certain positions of the limbs. This position is shown on the left of Figure 9. As the Back Revolute Joint (BRJ) is actuated, three other passive joints experience dynamic loads. These are the Hind Revolute Joint (HRJ), Middle Revolute Joint (MRJ) and Fore Revolute Joint (FRJ). This configuration of the model can therefore be reduced to the three bar linkage shown on the right of Figure 9. When two linkages are aligned, for small displacements, the system has an additional redundant D.o.F. that causes instability. Mechanical joint clearances in the physical model amplify this instability and thereby degrade climbing performance.

However, kinematic analysis showed that instability could be avoided by:

a) Increasing fore leg length
b) Decreasing hind leg length
c) Changing the motor position
d) Decreasing the rotation range of the BRJ

To maintain a symmetrical design for the RGR prototype, option d) was implemented in the physical model.

5.5 CGR Design

The RGR design is limited in its ability to be miniaturised by its use of DC motors and rigid links connected by pin joints. To enable small scale implementation in the CGR design, an innovative compliant structure and actuation system was conceived. Shape Memory Alloy (SMA) wire actuators that mimic the action of biological muscles actuate the composite frame of the robot. As shown in Figure 10, the robot back is flexible in this case, and is actuated by SMA wires on either side, a configuration that can be extrapolated simply to implementation at smaller scales. On the right side of Figure 10, a polymeric beam actuated by SMA wires is shown– this component was at the foundation of several prototypes that has been designed and tested by the authors.

The robot geometry was optimised to maximise robot step length and effectiveness of the SMA actuators. Analytical kinematic equations based on large deflection theory (Howell, 2001) were derived to enable step optimisation, accounting for the characteristics of a flexible back (Menon & Sitti, 2006). Maximum contraction of the SMA material was set at 4% of its length. In analysis of the robot back deflection, the CGR back was modelled as a cantilever with an external normal force R with a moment M applied to its end as shown in Figure 11. R and M are calculated iteratively since they are both functions of the cantilever deflection.

An iterative computational process was employed to calculate the force exerted with changing displacement for different values of s, which is the distance between the attacking point of the SMA wire and the axis of symmetry of the robot back (Menon & Sitti, 2006). Realistic data were used for the robot back; Young's modulus = 226 Gpa, back length = 10 cm, back width

= 24 mm. Control strategies may be designed through use of these results, in particular, a feed-forward control loop. Dynamic forces and weight were neglected in this analysis, since the CGR is intended to be light and to move slowly.

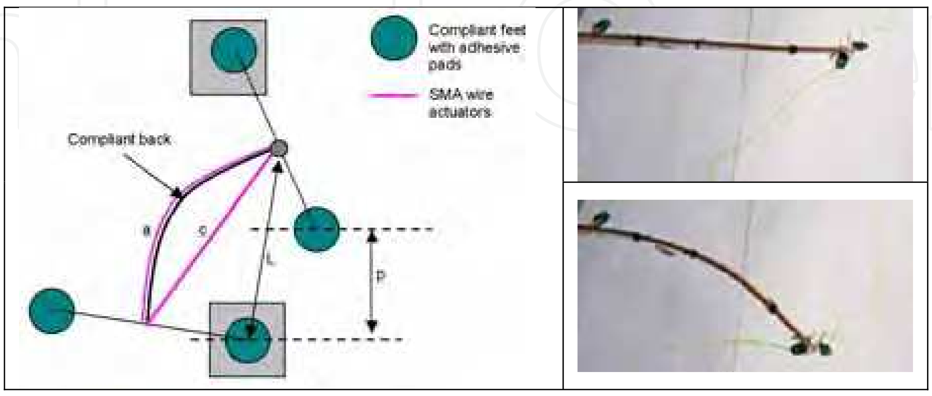

Figure 10. Model of compliant gecko-inspired robot

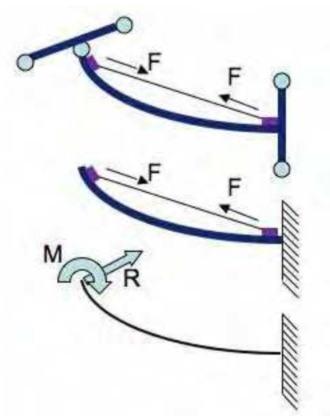

Figure 11. Model for the SMA force analysis. The CGR can be reduced to the study of a cantilever contracted by a SMA wire

5.6 RGR Prototype

The RGR chassis was constructed using aluminium alloy. Folded aluminium sheets were used for the frame. 5 DC motors were used, with four for lifting and planting of the legs and one in the robot back for locomotion. These 5 V motors generated 25 N mm torque each, making use of 81:1 gearboxes. Control was effected using a PIC 16F877 micro controller integrated with a customised electronic board. For robust and reliable motion, locomotion was implemented such that only one foot detached at any one time, with different legs detaching in sequence.

5.7 CGR Prototype

The CGR physical model's construction was considerably more challenging than that of the RGR due to the use of SMA actuators and a composite structure. The composite chassis was constructed in three layers:

1. Unidirectional prepreg glass fibre 30 μm thick (S2Glass)
2. Prepreg carbon fibre weaves (M60J), 80 μm thick
3. Unidirectional glass fibre (S2Glass), 30 μm thick

Glass fibre was used to both electrically isolate the CGR frame when in contact with the SMA wire and to reinforce the compliant structure. To augment the electrical isolation, a thin layer of epoxy was spun on over the robot back. The mechanical properties of this back laminate were calculated using the theory of mechanics of composite structures.

The final robot back measured 24 mm by 120 mm, and was actuated by six 50 μm diameter SMA wires (Flexinol® High Temperature SMA wires), with three on each side. Three composite material failure theories were employed in the verification of the structure when actuated by the SMA wires, Tsai-Hill, Hoffman, and Tsai Wu (Daniel & Ishai, 1994).

A larger number of thin wires were used in preference to a minimum number of thicker wires to increase convection effects during the wires' cooling phases. An external power source was used for the wires' heating phase, during which maximum contraction of these 100 mm long wires was 6 mm. Leg actuation was achieved with 100 μm diameter SMA wires with thermal cycle rates of 0.7 cycles s^{-1}. Leg configuration allowed the use of 14 mm long wires that were able to lift the feet up to 5mm away from the surface. The MRJ was implemented as a compliant joint fabricated from PDMS.

Appropriate methods of attachment had to be considered for the interface between the jump connections of the heating device and the SMA wires since soldering could not be employed; the heat involved in soldering might damage the SMA lattice. The first method involved connection of the SMA wire to the robot back using epoxy resin, compatible with the composite material of the back. The jump connector was then attached to the SMA by means of a lead crimp, allowing an electrical connection. The alternative method was to employ a frictional connection by means of a Delrin® hollow tube and metallic pin, to which the jump connector may be soldered. This second method was chosen for lower weight and greater reliability.

5.8 RGR Testing

The characteristics of the RGR motion are shown in Table 1. The maximum speed achieved of 20 mm•s^{-1} was a limit imposed mostly by the software employed. Modification of the control law was expected to lead to a climbing speed of 60 mm s^{-1}. Robust motion was observed while walking horizontally, while the robot was also able to climb in any direction on a surface inclined at 65° to the horizontal. While the robot had the potential to climb on vertical surfaces, the lack of encoders for feedback control of leg positions caused shocks and large amplitude vibrations. Such encoders could also reduce power consumption as motors could be turned off when the legs are not in use, since power is only required during attaching and detaching phases. Use of this strategy would lead to a power consumption of 130 mW.

Weight (g)	80
Length (m)	0.1
Width (m)	0.1
Speed (mm s^{-1})	20
Power consumption (mW)	360
Slope angle (deg)	*65*

Table 1. Performance and characteristics of RGR

5.9 CGR Testing

Static and dynamic tests were performed on the CGR to allow characterisation of the compliant back under actuation. A laser scan micrometer with resolution of 2 μm was used to measure the back deflection during actuation with the SMA wires.

Force exerted by the SMA wires is proportional to the voltage applied, and in a steady air environment, the force exerted is proportional to the temperature of the wire (Otsuka & Wayman, 1998). Furthermore, Eqn 1 shows the relation between temperature and voltage for an SMA where ρ is the resistance of the wire, D is its diameter, V is the applied voltage and a_1 and a_2 are empirical constants. Since a_1=0.7 and a_2 = 0.006, it can be seen that the second term can be neglected for small voltages and that temperature is proportional to voltage. Experimental results (Menon & Sitti, 2006) were used to validate the computational model presented in section 5.5 The model developed may be used in the development of a feedforward control law for prediction of the behaviour of the compliant back.

$$T = a_1\left(\frac{V}{\rho D}\right) + a_2\left(\frac{V}{\rho D}\right)^2 \qquad (1)$$

Dynamic behaviour of the robot back was observed using three different voltages. Experimental data show that:

a) for continuous cycling of the SMA actuators, cycle time is ~1 s
b) changing the applied voltage from 4 V to 6 V increases back displacement by only 0.5 mm
c) the cooling phase is dominant in the cycle time
d) increasing voltage causes a jitter effect in the displacement (Menon & Sitti, 2006).

Figure 12. The CGR prototype

It is therefore postulated that the minimum voltage that produces the desired displacement should be used for this system to avoid jitter in the displacement, while also minimising power consumption. Instability in the motion is observed when 5V is applied to the actuators. This is due to the dynamic behaviour of the SMA coupled with the compliant back. Acceleration of the back by the SMA causes a temporary dominance of the inertia of the back over the back elastic force, causing a vibration. This first oscillation is interrupted by the action of the wire actuator, leading to another contraction of the back. This instability may be overcome by either increasing the damping of the back. In Figure 12 the prototype actuated by SMA wires and built using carbon fibre composite is shown. Table 2 shows the characteristics and performance of the CGR.

Weight (g)	10
Length (m)	0.1
Width (m)	0.1
Slope angle (deg)	65

Table 2. CGR characteristics and performance

6. Future developments

The robots and synthetic adhesive designed and tested by the authors show the potential for the future development of climbing robots for industrial use. In addition, gecko inspired adhesive has great potential for space applications, with adhesion being largely surface independent, energy efficient (passive adhesion) and also suitable for low pressure environments (the adhesive was tested in a vacuum chamber). However, considerable future development is needed to obtain a fully functional, reliable and autonomous system.

For higher performance a nanoscale structure can be built on the top of the micro-scale synthetic filaments. Several technologies could be considered for fabricating or growing nano-hair. One possibility is to use nano-carbon-tubes, but tests performed by the authors shows that they are intrinsically brittle - their implementation in climbing robots has not shown, to the authors' knowledge, any successful implementation yet. Another possibility could be to implement a nano-moulding technique similar to the micro-moulding technique described in previous sections. In Figure 13 a moulding technique is presented.

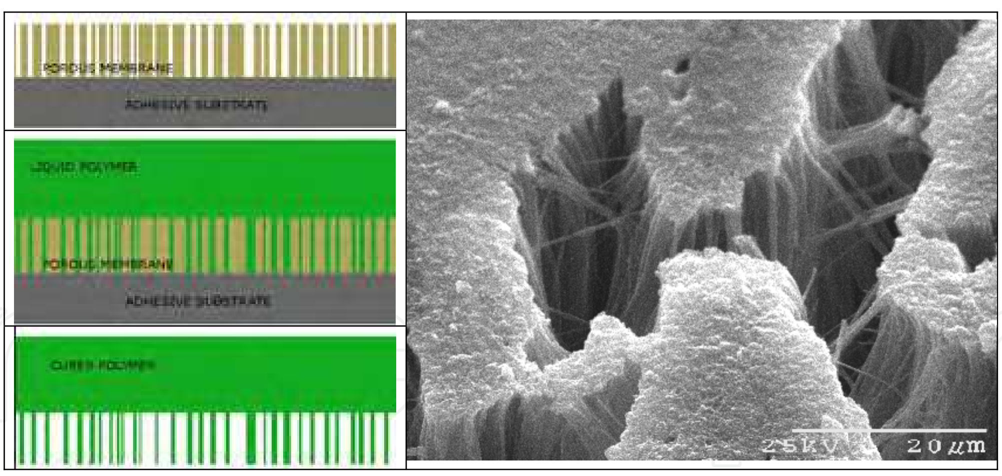

Figure 13. Nano moulding technique and Scanning Electron Microscope (SEM) image of the results

A nano-porous membrane is attached to an adhesive substrate, a liquid polymer is poured on the membrane and is thermally cured, and is subsequently peeled off. A membrane could have pore size of 0.02-20µm, thickness of 5µm, and pore density of 105-108 pores/cm^2.

By using an alumina membrane, nano-hairs with a diameter of about 200 nm were produced. Figure 13 presents the results and shows that fibres are bunched and matted. This is mainly due to the long length of the nanofibers and to the too soft fiber material, which was used - surface force is very high at this scale and should be carefully taken into account both during the fabrication process and use of nano-hairs. Research is still in progress and the authors are confident that soon a gecko inspired dry adhesive having both micro- and nano- fibres will show robust performance on climbing robots.
As far as the robotic system is concerned, future research is aimed at developing a gecko inspired compliant robot that could efficiently climb up and down vertical surfaces, be able to transfer between surfaces at different angles and incorporate embedded sensors, power system and a bio-inspired controller for full autonomy. In Figure 14 the frame of a truly compliant legged gecko robot prototype obtained by moulding technique is shown.

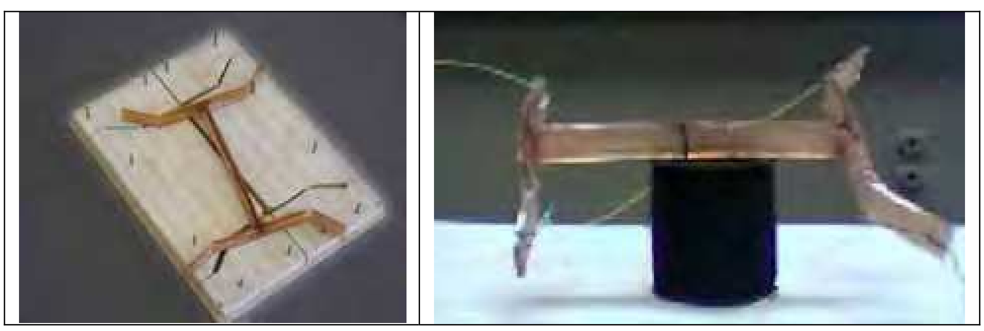

Figure 14. Frame of a compliant gecko robot

The design of the robot should also take into consideration the space environment in which it will operate. The design of a climbing robot that could be qualified for operating in space has not been performed yet. In particular a very detailed study of the use of SMA as primary actuation system should be carried out - preliminary computation shows that radiation could be sufficient for cooling of micro SMA wires in space during sun occultation. However their use as primary actuators in a legged locomotion system for planetary exploration has not yet been addressed by the authors. Power consumption will also be a critical issue.

7. Conclusions

The potential advantages of gecko-inspired robots have been discussed and related to the particular problems of robotic systems in space. Different approaches to climbing robots in general have been introduced and, in particular, differing approaches to gecko-inspired systems have been discussed.
The phenomenon of dry adhesion in nature has been introduced, along with methods for its recreation in engineered materials. Different designs for robots intended to take advantage of gecko-like dry adhesion have been conceived and prototyped, showing potential for further development. In particular, one design has been focused on the realisation of a robust and reliable system, while the other, using novel materials and actuators, has potential for miniaturisation. Potential future development work has been identified.

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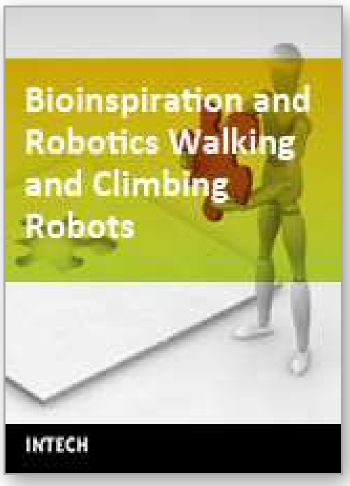

Bioinspiration and Robotics Walking and Climbing Robots

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Nature has always been a source of inspiration and ideas for the robotics community. New solutions and technologies are required and hence this book is coming out to address and deal with the main challenges facing walking and climbing robots, and contributes with innovative solutions, designs, technologies and techniques. This book reports on the state of the art research and development findings and results. The content of the book has been structured into 5 technical research sections with total of 30 chapters written by well recognized researchers worldwide.