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Bio-Inspired Landing and Attachment System for Miniaturised Surface Modules

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ABSTRACT

The study proposes a biologically inspired concept to land and firmly attach swarms of miniaturised satellites or probes to the surface of low gravity objects. The probes are shot at relatively low speed towards the surface of the body to which they are fixed using a combined and miniaturised damping and attachment system, inspired by the dry-adhesion of geckos and spiders. When compared to more traditional fully controlled landing systems, this solution promises to provide a high payload to mass fraction while reducing system complexity. A preliminary design of the landing system is presented and the most critical issues are discussed.

1. INTRODUCTION

Future space science missions aimed at characterising the geophysical properties of asteroids and comets could benefit from employing a number of miniaturised surface modules distributed at different locations of the celestial body and performing collaborative measurements [1,2]. This is closely related to the concept of having a distributed network of sensors flying in formation along a nominal orbit or in free fall to perform a given scientific task (e.g. high spatial resolution measurements of a planet atmosphere [3]).

One of the technical challenges of a distributed sensor approach for asteroids exploration is represented by the need of landing and securely attaching the modules to a prescribed spot on the surface of the target body.

Up to now, the demanding task of soft landing a probe on asteroids has been attempted four times with two failures. In 1989, during the last phase of the Phobos-2 mission, the two modules due to land on Phobos' surface were never released from the main spacecraft due computer problems. Later, in 2001, the Near-Shoemaker spacecraft (about 500 kg of mass) successfully landed on the asteroid Eros and remained operational despite the estimated impact velocity of 1.5 to 1.8 m/s. More recently, in November 2005, the MINERVA mini-spacecraft, weighting less than 600 g, was released from the Hayabusa spacecraft while hovering on asteroid 25143 Itokawa. Unfortunately, the mini-lander never reached the surface of the asteroid due to a control problem [4]. Nevertheless, the more massive (about 400 kg) Hayabusa mother spacecraft successfully performed a series of soft landings with the asteroid.

When dealing with small asteroids like Itokawa the landing and attaching process is complicated by the extremely low gravity of the object (Itokawa has a surface gravity of only 10 μg). In this scenario, without an onboard propulsion system to compensate for reduced gravity conditions, a small error in the release velocity of the probe from a mother craft can cause it to miss the asteroid or to impact it in such a way that the bouncing velocity will make the probe escape from the asteroid's tiny gravitational field. Besides, in some cases of fast rotating asteroids the centrifugal acceleration on the surface may considerably reduce or even exceed local gravity, thus complicating the attachment phase.

Certainly, these issues can be tackled by increasing the number of sensors and actuators onboard but this will have an impact on the mass budget that is often unacceptable. In particular, when miniaturised surface modules are employed, sensors and actuators have to be reduced to an absolute minimum in order to deliver as much payload mass as possible.

In this framework, a source of inspiration to ease the achievements of these goals is offered by biological systems.

The growing recognition of biomimetics, the practice of 'reverse engineering' ideas and concepts from nature [5], as a powerful alternative approach to typical engineering problems has slowly started to influence space system design.

For our particular application, the use of dry adhesive techniques employed by geckos and spiders could turn out to be very advantageous for a number of reasons. First, the adhesive is by its nature a high force density actuator (forces of several newton per centimetre square have been obtained with nano-fabricated tape of negligible mass). Second, if surface mobility is not required (as in our case) the dry adhesion system becomes a completely passive actuator. Third, it potentially offers great flexibility and adaptability to different terrains and surface conditions.

The novelty of our approach is to combine the dry-adhesion attaching system with the ballistic delivery of microprobes on the surface of a low-gravity body. In this way, the properly tuned kinetic energy at the impact can provide the preload required to increase the strength of the adhesive system by many folds. The combination of these might be a suitable approach to meet the hard constraints and particularities related to the landing of small probes on low-gravity bodies.

1. PROBLEM DEFINITION AND PROPOSED APPROACH

Let us consider a scientific exploration mission to a small asteroid or comet based on a set of miniaturised surface modules equipped with different sensory capabilities and possibly cooperating with each other to perform a given scientific task. Assuming the modules are initially stored on a mother spacecraft orbiting or hovering at a specific distance from the body, we focus on the problem of safely delivering the modules at specific spots on the surface.

In this framework, our goal can be stated as follows: design a landing and attachment system strategy in order to distribute a series of miniaturised surface modules on determined locations of the asteroid/comet while maximising the payload to mass fraction and minimising

the operational complexity of the landing phase.
For this purpose, we propose to ballistically shoot the different micro-landers towards the low-gravity body, and suggest a biologically inspired concept to assure reliable surface attachment for subsequent operation.

2. BIOLOGY SOLUTIONS FOR LANDING

2.1 Geckos' attachment system

Tokay geckos (*Gekko gecko*) reliably adhere to nearly any solid material surface under most environmental conditions and almost independently of its texture, physical and chemical properties [6-9], even including water immersion, ionized air, nitrogen atmosphere, and space vacuum.
This phenomenon of controllable adhesion is attributed to a hierarchically structured attachment system, as morphologically detailed in e.g. [6-9]. Each foot has five toes that ventrally bear adhesive pads uniformly covered by setae, i.e. micro-structured arrays of hair-like keratinous bristles, grouped in up to 20 lamellae, as shown in Fig 1 (a,b). Setae again are distally branched into up to thousand of finest extensions (spatulae). Their triangularly broadened distal ends, in the length order of 200 nm, finally constitute direct contact with the substrate. Resistance to contamination, involving anti-adhesive, anti-fouling, self-cleaning capabilities [6,7,10], and directional stickiness are other key features.
Akin spiders and unlike many insects geckos lack secretory glands, exclusively relying on dry adhesion. Thus, their dry grip evidently is dominated by van-der-Waals forces mediated through the increased number of contact points with the substrate. Owing to the soft cuticule matrix, the hairy system clings tightly to substrate contours adapting thus for varying degrees of surface roughness. Atomic Force Microscope (AFM) measurements quantified the mean adhesive force generated by one single isolated seta (normally preloaded with 2.5 µN) roughly ranging between 20 µN [11] and 40 µN [9]. Combined with a 5 µm sliding displacement parallel to the surface and a normal preload of 15 µN, mean friction forces of 200 µN can be reached, whereas higher preloads would result in local setal buckling [9]. For isolated few single spatula tips, pull-off forces averaging 10 nN have been recorded and a work of adhesion of 21 mJ/m² estimated [10].
Moreover, falling geckos can easily reattach to leaves, branches or trunks. Taking into account a 50 g gecko dropping by 10 cm from rest and reaching 1.4 m/s at attachment, the animal arrests after a 1.1 cm slide, while requiring only a fraction of the theoretical shear stress of single setae [6, 7].
To release their strong setae grip, geckos curl the toes up and away from the substrate, actively breaking the van-der-Waals forces [6-9].
A very important aspect of the gecko attachment strategy is the need for a preload on the attachment system in order to increase the contact fraction and produce a stronger surface interaction. The fact that geckos are able to move on vertical and inverted surfaces clearly shows that this preload is produced dynamically by accelerating the toe towards the surface.

3.3 Engineering prototypes and current challenges

The attachment mechanism of geckos has been scrutinized and several engineering prototypes of artificial reusable gecko-tape [12-15] have been conceived for various applications [6, 15,16]. Current advanced in fabrication of gecko adhesives and their specific limitations are synoptically detailed in [12]. Approaches based on nanomolding techniques [13] using polymer materials such as polyimide (PI), polyester, or silicone rubber, or microlithography methods in combination with plasma etching [15] resulted in nano-hairs with adhesion forces roughly matching those of biological ones; patches of PI hairs bonded onto a flexible backing layer could support almost 10 N/cm² [15].

Very recently, bundles of modified carbon nanotubes (CNTs) have been grown and transferred to a flexible backing plastic [14]. The resulting tape has experimentally proved to provide a shear stress of 36 N/cm², thus being stronger than all previously published dry adhesives, even four times topping the stickiness of natural gecko foot hairs. The SEM images of Fig. 1 illustrate the close similarity of natural gecko setae (B) with the synthetic ones of width 50 (C) and 100 μm (D), which again are branched into thousands of aligned CNTs averaging 8 nm in diameter.

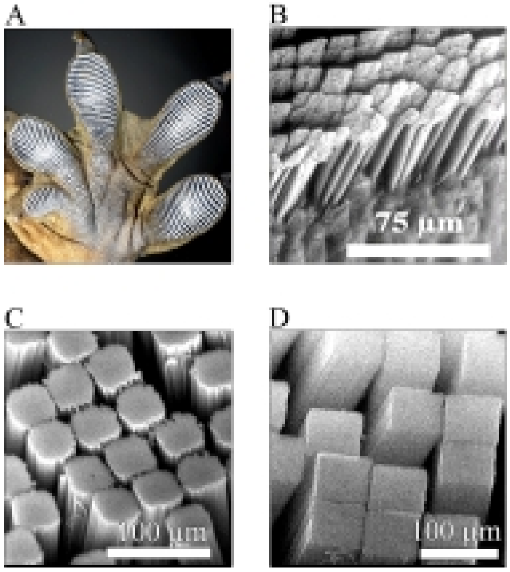


Fig 1: (A) Optical picture of a gecko foot showing the lamellar arrangement of the setae. (B) Scanning electron microscope (SEM) image of natural setae distally branched into spatulae. (C and D) SEM images of artificial setae indicating their spatular terminations. (©, with courtesy of A. Dhinojwala, University of Akron).

Another line of research on artificial dry-adhesive systems has focused on mimicking the multilevel conformal structure of the attachment system to increase surface contact and surface adaptability.

Northen and Turner [17] succeeded in manufacturing an organorod-based dry adhesive integrated into a compliant structure with significantly improved adhesion with respect to a single-scale system.

As adaptability to unknown terrain is paramount for asteroid attachment, the design of multilevel conformal adhesive structures may be key to the performance of the system.

3. LANDING AND ATTACHMENT SYSTEM: DESIGN AND MODELING

The first phase of the landing process will be to eject each micro-module from the mother spacecraft with an ejection velocity v_e to allow targeting a specific location on the asteroid. For instance, there may be an interest in having one or more modules landed on a scientifically interesting surface area or establishing an evenly distributed surface coverage with the different modules.

We propose passive attitude stabilisation of the module during the descent phase by inducing light rotation at the moment of ejection or by having a simple fast rotating internal gyroscopic unit to enhance the probe attitude stability. This strategy will allow having the probes impacting the asteroid surface with a known attitude and will aid to optimise the design of the energy damping subsystem.

Once each microprobe touches the asteroid surface a series of lightweight rods covering the respective contact surface of the craft in normal orientation will begin to interact with the asteroid surface. Depending on the strength and compactness of the asteroid material, the spikes will either penetrate it, resisting the impact load, or else will undergo instantaneous flexural or buckling plastic deformation, hence absorbing a portion of the energy of the impact shock.

In the first case, damping is achieved by the dissipation of kinetic energy through friction with the asteroid soil, while simultaneously ensuring a strong anchoring,exerting thus both preload and sliding displacement for interfacial contact and strong adhesion [6-9].

4.1 Microprobes' ejection

The choice of the ejection velocity (v_{ej}) is primarily driven by two considerations: The velocity should be high enough to contain the maximum error on the prescribed landing site but at the same time, its value should be limited by the maximum energy that the damping system is able to absorb or the maximum deceleration the probe can tolerate. Taking Fig. 2 as a reference the mother spacecraft is orbiting or hovering at an estimated altitude h from the surface and moving relatively to the asteroid surface with an estimated velocity vector $\mathbf{v}_{nom}$. Note that $\mathbf{v}_{nom}$ is determined by the orbital velocity of the mother spacecraft as well as by the rotation of the asteroid around its own axis, so in general $\mathbf{v}_{nom}$ is different from zero also for the case of a hovering spacecraft. The estimation errors δh and δ**v** are assumed for altitude and relative velocity, respectively. In particular, δ**v** may also include orbital or altitude correction manoeuvres performed by the mother spacecraft prior to ejection of the probe.

Assuming the micro-probe is released along the zenith direction and neglecting the asteroid's gravity, simple kinematic considerations provide both the estimated along-track (ε_{AT}) and cross-track (ε_{CT}) errors:

$$\varepsilon_{AT} = \frac{H}{v_{ej}}\delta v_x + \frac{v_x + \dot{\phi} r}{v_{ej}}\delta H - \frac{v_x + \dot{\phi} r}{v_{ej}^{\ 2}} H \delta v_{ej} \quad (1)$$

$$\varepsilon_{CT} = \frac{H}{v_{ej}}\delta v_y + \frac{v_y + \dot{\psi} r}{v_{ej}}\delta H - \frac{v_y + \dot{\psi} r}{v_{ej}^{\ 2}} H \delta v_{ej} \quad (2)$$

where v_x and v_y are the velocity components in the plane (xy) orthogonal to the asteroid local vertical, H is the mother spacecraft altitude, ψ and ϕ are the rotation of the mother spacecraft around the x and y direction (with x parallel to the nominal velocity) and v_{ej} is the ejection velocity of the module.

As expected, the higher the ejection velocity the higher will be the landing precision. On the other hand, too high an ejection velocity may exceed the energetic limits dictated by the damping and attachment system design.

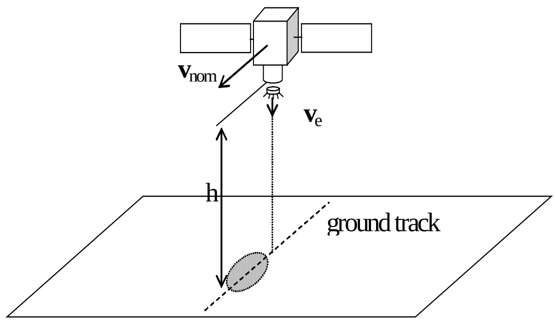


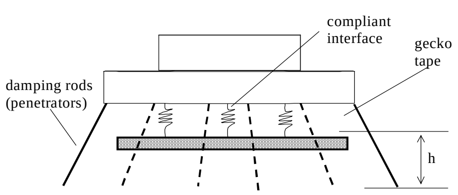
Fig.2 Schematic of microprobe delivering from mother spacecraft

4.2 Impact energy damping and attachment system

The key point in the design of the attachment system is its adaptability to a variety of asteroid surface morphologies and strength characteristics.
Asteroid surface properties can range between two extremes:

A) *Strengthless rubble pile*: the asteroid is an aggregate of cohesionless material held together by its (reduced) gravity alone. This does not mean that the asteroid will behave as a perfect fluid as in general material friction will be present.
B) *Solid rock:* the asteroid is a consolidate material with a given tensile and compressive strength which is considerably higher than the maximum stress induced by self-gravity.

The proposed solution to cope with such diversity is the combined presence of damping/penetrating rods and of a compliant synthetic attachment system on the impact surface (Fig. 3). Depending on the strength and viscosity characteristics of the asteroid surface compared to the mechanical stiffness of the rods, the latter behave either as penetrators or as pure energy dampers. In the first case, the probe kinetic energy is absorbed through friction with sand-like soil, while in the second it is absorbed by the plastic deformation of the spikes.



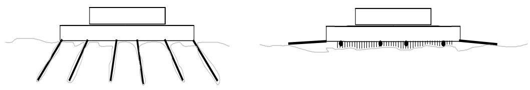


Fig.3 Schematic of microprobe combined damping/attachment system and final configuration depending on asteroid strength (rubble pile on the left, consolidated material on the right)

The modelling of the penetration dynamics, for the case of very low strength asteroids will be aimed at in a separate future study. Experimental penetration tests, more than analytical and numerical investigations, are likely to provide important answers to this design problem.

In the case of stronger asteroids, the focus of the design moves to the issue of absorbing the impact energy through plastic deformation of the rod-like appendages assuming the asteroid infinitely rigid. The impact dynamics for these kinds of problem can be very complex. Nevertheless, a simplified analysis can help in the preliminary design of the system. Since the impact speed will be relatively low, a quasi-static assumption can be made for the elasto-plastic deformation following the impact. Relatively low impact velocities (say <2 m/s) are reasonable provided that the altitude from which the probes are shot is sufficiently small.

By equating the kinetic energy of the probe to the strain energy of the damping system we obtain:

$$N\sigma\varepsilon A\ell = m{v_e}^2 \qquad (3)$$

where N is the number of rods, σ the load stress of the individual rod, ε its deformation, A the cross section and ℓ its length.

For example if the rods react by axial deformation Eq. 3 yields the maximum tension at impact as:

$$\sigma_{\max} = v_e \sqrt{\frac{mE}{NA\ell}} \qquad (4)$$

The condition for plastic deformation is then:

$$v_e \sqrt{\frac{mE}{NA\ell}} >> \sigma_Y \qquad (5)$$

where σ_Y is the yield tension of the material. Eq. (5) shows that a reduction of contact area promotes plastic behaviour in the damping appendages. On the other hand, longer roads tend to reduce the maximum tension and prevent plastic behaviour. Yet having relatively long rods is beneficial for reducing the payload maximum deceleration by prolonging the impact duration.

The consequence of plastic behaviour on the impact dynamics can be quantified through the coefficient of restitution $0 \leq c \leq 1$:

$$c = \frac{W_{el}}{E_k} \qquad (6)$$

which corresponds to the ratio of elastic energy stored in the system over the total kinetic energy of the impact.

An optimal value of stiffness of the gecko-tape compliant interface can be obtained which provides a desired value for the synthetic adhesive preload. By modelling the interface as a rod of length ℓ_l, Young modulus E and cross section A_i the analogous of Eq. (4) provides the maximum tension acting on the tape:

$$\sigma_i = v_i \sqrt{\frac{mE_i}{A_i \ell_i}} \qquad (9)$$

where v_i is the impact velocity of the gecko tape with the asteroid surface.

By having σ_i as close as possible to the necessary tape preload attachment conditions can be optimised.

4. CONCLUSIONS

We proposed a simple and cheap strategy to efficiently and accurately deliver a number of miniaturised lander moduli on prescribed locations of low gravity bodies such as asteroids or comets. As our preliminary analysis has shown the need for targeting accuracy and reliable attachment on the unknown target surface may be met by ballistically ejecting the microprobes towards the surface and by employing a damping/penetrator mechanism coupled to a bio-inspired dry-adhesive system.

The difficulty of adapting the design system to various surface conditions may be best tackled with more refined modelling of the impact/penetration dynamics accompanied by extensive ground testing which is made considerably easier by the small size of the microprobes and relative simplicity of their design.

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