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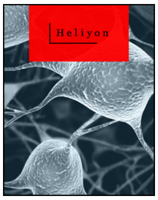

Review article

Towards bio-inspired robots for underground and surface exploration in planetary environments: An overview and novel developments inspired in sand-swimmers

A.J.R. Lopez-Arreguin *, S. Montenegro

Informatik VIII, University of Wuerzburg, Germany

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ABSTRACT

Dessert organisms like sandfish lizards (SLs) bend and generate thrust in granular mediums to scape heat and hunt for prey [1]. Further, SLs seems to have striking capabilities to swim in undulatory form keeping the same wavelength even in terrains with different volumetric densities, hence behaving as rigid bodies. This paper tries to recommend new research directions for planetary robotics, adapting principles of sand swimmers for improving robustness of surface exploration robots. First, we summarize previous efforts on bio-inspired hardware developed for granular terrains and accessing complex geological features. Later, a rigid wheel design has been proposed to imitate SLs locomotion capabilities. In order to derive the force models to predict performance of such bio-inspired mobility system, different approaches as RFT (Resistive Force Theory) and analytical terramechanics are introduced. Even in typical wheeled robots the slip and sinkage increase with time, the new design intends to imitate traversability capabilities of SLs, that seem to keep the same slip while displacing at subsurface levels.

1. Introduction

In all air, ground or water living creatures, the locomotion is governed by the physics of the medium in which the body, composed of nervous and musculoskeletal systems of multiple degrees of freedom [1], bends and flows generating thrusting forces that normally outcome frictional forces. The net forces generated by small organisms enable to propel themselves from accelerating fluids in large swimmers [2], and in others like snakes ground reaction dynamics provides thrust. It was in this framework that physicists dedicated to study the mechanics of animals in granular mediums, realized the manner those organisms are able to use their body undulation to generate locomotion capabilities, could be important for designing strategies for robots to move along loose soils [3, 4]. Nonetheless, this has required a high degree of understanding not very well consolidated yet [5, 6]. This short paper serves as overview on the basic mechanisms for bio-inspired underground and surface robots, proposing a new adaptation of the novel discoveries in the field of sandfish mobility to improve capabilities of future exploration wheeled robots. Section 2 features the most promising reports on bio-inspired locomotion systems performed up to date, that can find applicability to planetary exploration. Section 3 presents the necessary theory of sandfish animals and rolling, for addressing within Section 4 the proposed surface locomotion mechanism.

2. Biologically-inspired mechanics for underground and surface robots: space and terrestrial developments

Biologically-inspired robotics is a field primarily driven by observation and reproduction of the locomotion principles found in nature [7]. Even almost all robotic systems are inspired (in one way or another) from biological systems [8], bio-inspired robots is a term coined to a broad classification of robot types, based in the models of motion that animals use to survive in their natural habitats [9]. Among these we can find, in general, surface robots (limbed and limbless systems), flying robots, swimming robots (moving in water bodies or fluids) or subsurface robots (swimming in granular media) [9]. Even uncountable examples of locomotion exist in nature, and robotic reviews on that are found elsewhere [8, 10, 11], most surveys on space robots [12, 13, 14] are not focused on bio-inspired hardware. Therefore, biologically-inspired robotics involves a wide number of remarkable developments

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* Corresponding author.
E-mail address: amenosis.lopez@uni-wuerzburg.de (A.J.R. Lopez-Arreguin).

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(e.g. as [1, 15, 16] or [11]) that still not connected to the field of planetary exploration, and hence missing in most space reviews. And from the existing literature on bio-inspired explorers, we find surveys limited to agency roadmaps [17, 18, 19], or to robots facing a particular environment, either subsurface [20, 21, 22], surface [23, 24, 25] or aerial exploration [26, 27]. Therefore in this section we try to address the most recent worldwide efforts on robotics, that drawing inspiration from nature, are taken to develop more robust concepts for surface exploration (legged or limbless robots), or subsurface equipment (penetrators, excavators). Previous related hardware deployed in space missions is in some cases briefly summarized, with the aim to illustrate the advantage of adopting biological locomotion principles in future space initiatives.

2.1. Surface vehicles

2.1.1. Limbed robots

Multi-legged systems. Legged robots are systems in which their limbs are used as active suspensions allowing to decouple the main robot body to the roughness of terrain [28]. Although legged robots are maybe one the oldest and most developed bio-inspired systems available nowadays, they inner complexity require extensive hardware performance (as energy, actuation, robustness, stability, etc.) to demonstrate true animal-like locomotion capacity and hence be successful in unstructured environments [29]. These characteristics make wheels or tracks better suited than legs for extraterrestrial applications [28]. Nevertheless, spider-like limbed systems are finding nowadays more diverse applications as secondary (supporting) units, deployed typically from larger rover vehicles to perform exploration in sites of difficult access, like gullies or craters [30, 31, 32]. On the other hand, distinct space agencies have seen an opportunity to combine limbed locomotion with other systems (e.g. wheels or tracks), proposing novel hybrid robots for challenging scenarios. This type of concepts are being designed for surface vehicles on the Moon (ATHLETE [33] or Sherpa [34]) or as service robots to support astronauts (as JUSTIN [28]).

2.1.2. Limbless robots

While locomotion based in limbed systems results from legs pushing the ground, limbless robots tend to imitate crawling locomotion, in the sense that body motion alone allows progression [35]. Robot models based in limbless animals are seen as prospects for future exploration initiatives for both surface vehicles or sub-surface research. In particular, here we will treat designs with better aptitudes for autonomous surface exploration, based on inchworms, earthworms or snakes principles.

Inchworms These animals typically achieve a propelling motion by propagating a forward wave generated from a looping movement, in which the anterior legs and posterior legs are alternately made fast and released [35, 36, 37]. Relying on the inchworm motion, researchers have devised robotic modules for accessing very complex geological landscapes regardless the gravity environment [38]. Such robots have the ability to propel themselves along any direction in a three-dimensional space, either climbing vertically or traversing irregular surface profiles [39]. Hence they are typically divided in several joint mechanisms with strong grips [40], for which progression around any arbitrarily oriented surface is achieved by alternation of fastening [36]. These come in either soft-design robots [41, 42] or rigid units [43]. For the first, remarkable experiments have featured inchworm robots made of soft materials (e.g. typically silicone or pneumatic muscles made of elastomerers), but one important research direction is adapting these novel architectures for applications into complex surface environments. To our best of knowledge, no research on this sense has been addressed yet. With regard to rigid inchworms robots, sophisticated robot concepts based in caterpillar mechanics are being proposed for accessing cliffs and lava tubes of rocky Mars or the icy environments of Enceladus or Europa [44].

Earthworms Earthworms move by a locomotion mechanism called peristaltic crawling, which works by propagating a longitudinal wave from the front of the body to the back by varying the thickness and length of its segments [45]. Similarly as inchworm mechanics, peristaltic crawling robots allow for movement across narrow spaces and irregular ground [46], and can be composed of rigid or flexible joints [47, 48]. Latest developments [49] feature units made of flexible plates and soft actuators that can expand or contract in the radial direction, analogous to the motion generated by the circular muscles of earthworms. The mechanical units generate extension and contraction waves that propagate from the anterior to posterior part of the robot, resulting in a net thrust. Although several models have been proposed, in general earthworm-type robots require of very narrow spaces for traversing, making them more ideal for subsurface exploration where probe diameter is proportional to the propulsive resistances exerted by the soil against motion [50]. On the other hand, engineers have found inchworm-type robots to have superior locomotion capabilities than earthworm-based systems in traversing flexible surfaces, offering higher displacements and lower frictional loses under most circumstances [51]. However, with regard to our focus, current research is insufficient to decide the best choice for traversing complex environments made of granular media. Earthworm-type robots feature no clamping mechanisms, simplifying much of the robot design and also saving much of the energy loss associated with the unclamping stage. Each bio-inspired worm-type robot can be more suitable to explore specific planetary environments that not necessarily need to be the same.

Snakes Snake robots are the most popular limbless robotic systems and have become an active research topic for decades [52, 53, 54]. Snakes typically generate locomotion by curving their own body and pushing it against the relief, in a way that the reaction forces constitute the total propulsive force required for progression in a given direction [55]. Hence robots are often made of several segment units connected in a very modular manner, with high flexibility and a slender shape [10, 56, 57]. Since the introduction of snake robots in the 1970s by Hirose et al. [53], most subsequent designs have been tested on rigid surfaces [10], while very few on unstructured environments [58, 59]. But conventional snake robots feature several drawbacks, in particular related to control their motion due to their many degrees of freedom (DOF) [60], or becoming problematic in traversing very narrow spaces [56]. Therefore, researchers have been seeking to improve conventional drawbacks of snake robots, in particular related to control their dynamics, which becomes problematic in traversing very narrow spaces. One form to address the previous is to update snake robots using wheels [10], or more recently using Archimedean screws [56, 61]. Regarding the latest, the proposed solution gets its heritage from the amphibious terrestrial vehicles developed since the 19th century for high trafficability (in snow, ice, mud, etc.) [62, 63], replacing the typical snake undulation movement with a propulsion generated through rotation of the screw units. With this, a new type of surface rovers have been proposed inspired in screw-driven snakes [64], showing remarkable advantages as becoming almost insensitive to slip phenomenon and getting stuck in soil [50]. After these successful examples, the European and Japanese Space Agencies have started to propose snake-like rovers for improving traditional wheeled or tracked robots in surface exploratory activities [4, 65]. Nonetheless, future use of snake-like robot architectures will require to count with lightweight materials, which still an important focus for future research.

2.1.3. Subsurface locomotion

Subsurface analysis of a planet, comet or an asteroid can provide understanding of their geologic composition and body history. In light of the previous, subsurface robots are seen as a promising tool for having insights into the evolutionary history of the solar system, or achieving top science goals as the search for life [66]. One of the earliest missions to carry out drilling experiments in extraterrestrial surfaces were the

Apollo 15, 16 and 17, which used mainly hammer-driven core tubes and rotatory percursive drills to collect samples up to depths of 3 m [67]. These experiments were crucial in our understanding of the existing celestial bodies, showing us that even surface regolith is highly compressive, bottom layers beyond 10 cm exhibit high compaction and are difficult to excavate [68]. Some older soviet landers as Luna 16, 20 and 24 reached 1.6 m below the lunar surface [69], while Lunokhod 1 and 2 rovers carried a cone-vane penetrometer to access distances of up to 0.1 m [70]. Drills mounted on landers or robotic equipment have made some tasks at shallow depths on Venus (Venera 13-14 and Vega 2 landers [71]), or performed scooping on the Moon (Surveyor 3 and 7 [50]) or Mars (Viking landers [72]). More recently, space drilling activities took place onboard the Rosetta [73] and Beagle 2 [74] landers and in the Curiosity rover [75]. Newer experiments deployed on Mars are designed to collect samples up to 5 m depth onboard the Insight mission [76], and other similar drills have been devised to penetrate up to 2 m onboard the Exomars 2020 rover [77]. Now, it is important to notice previous boring systems feature similar characteristics: (a) devices are typically self-propelled by internal hammering mechanisms and rotatory drilling techniques (except those operated by hand in the Apollo program), (b) they have been deployed in relatively loose regolith and covered short distances, and (c) commonly had difficulties to penetrate hard rocks or very compact regolith. Hence a new generation of systems capable to access larger depths ($\gg 10$ m) are being proposed, based in tethered or autonomous penetrometers and excavators [66, 78]. Considering that compressing of regolith is an impractical technique for locomotion at the required (higher) depths in the Moon or Mars (a lunar probe would require to generate few hundreds of kilo Pascals to go as deep as 1 m [50]), researchers are developing hybrid systems able to perform fore-soil removal while using principles of bio-inspired locomotion to generate the main propulsive forces. With this, many subsurface robots have been designed having the ability to reproduce the mechanics of inchworms, earthworms, wood wasps or gophers, while being complemented with strong drill stems that can brake hard fore-regolith and transport it backwards. These designs drawing inspiration from nature are briefly condensed in the following.

Inchworms Subsurface probes based on inchworms are today one of the most successful sampler technologies for autonomous deep access, overcoming traditional penetrometers and drilling systems within depths of up to 0.1-10 km [66]. The Inchworm Deep Drilling System (IDDS) [79] of NASA/Honeybee is capable of drilling granular media, rocks or ice as Mars or Europa. Other successful example is the Inchworm Boring Robot (IBR) [80] that was proposed for China's lunar robotic subsurface exploration mission. In general, this kind of probes reproduce the inchworm locomotion to walk down into the borehole, while a drilling head is in charge of removing fore-regolith.

Earthworm Similarly as inchworm-type robots, these subsurface systems rely on a bio-inspired propulsion system, guided by a second unit in charge of excavation (drilling unit) [81]. The earthworm locomotion principle provides a good stability to the excavator, maintaining the robot body position and orientation while avoiding lateral deviations [82]. Peristatic crawling reduces the friction when compared to other worm-based systems. Nevertheless, the few prototypes available still cannot demonstrate excavation at large depths beyond 1 m [81], becoming an important focus for future research.

Wood wasp A bio-inspired penetrator based on the working mechanism of wood wasp ovipositors have been proposed [78, 83]. This kind of animals use a reciprocating motion of two halves with backwards-facing teeth to drill into wood in order to lay its eggs [84]. By fixing very well their teeth at the inner stem, wood wasps can generate a traction force by moving half of their teeth backwards. This reversing half encounters a resistance by the stem support, which is converted to an additional force for the penetrating half, while eventually overcomes the required force to drill [85]. Based in this principles, the dual-reciprocating drill (DRD) prototype has been proposed. The DRD features a light-weigh system, small dimensions and higher energy efficiencies comparable to other drilling systems [78]. Besides, it avoids the need of external forces driven by hammer mechanisms in typical penetrators. Unfotunately, this bio-inspired system is unsuitable to penetrate rocks or highly compressed regolith, although they are convenient for subsurface exploration in shallow depths on loose regolith [80].

Gopher The gopher can form underground tunnels by making holes with their limbs and removing soil along its path. A system called auto-gopher has been proposed [86] for subsurface exploration of planetary bodies. It consists on a wireline drill that can be lowered and raised via a tether, and a separate mechanism that removes fragments and cuttings [87]. The Auto-gopher has been successfully tested in a laboratory environment in rock to a depth of 3 m [86, 87].

Undulatory swimming Undulatory locomotion is the self-propulsion of an organism via the passage of deformation waves along its body [15]. In this category we find many subsurface robots imitating desert organisms that can burrow and swim in sand, as snakes, scorpions or lizards. While studying sandfish lizards, Maladen et al. [1] reported the outstanding feature that these animals are not reliant of their limbs as mechanism for subsurface locomotion (they only use them to bury fastly on sand). The sandfish use a limbless propulsion system very similar to snakes, that allows to swim and move forward developing undulatory patterns with their body [16]. Inspired by this behavior, Maladen et al. [88] assembled a 7-link sand-swimming robot to imitate lizard locomotion. The robot was able to form a sinusoidal traveling wave pattern and achieved speeds of up to 0.3 body-lengths per cycle of oscillation [58]. Experiments allowed to correlate this bio-inspired mobility with theoretical models and other techniques, and study the actual performance of lizards under soils with distinct relative densities [89].

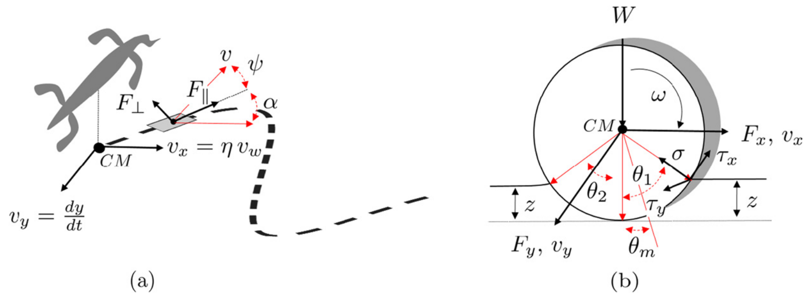
Now, with regard to planetary exploration, the high compaction found in bottom regolith layers of extraterrestrial surfaces, suggests that subsurface slithering locomotion associated to lizards may have more potential for surface robots operating in shallow depths than for soil penetrators. This is because subsurface excavators based on worm principles are highly suitable to access larger depths independent from the gravity environment [66], finding applicability in a broader spectrum of geological features (either soil, ice or rocks) while requiring only modest amounts of power [79]. Nevertheless, more research needs to be done to clarify the capabilities of robotic equipment based on lizard principles for planetary exploration. Considering the previous, this paper intends to recommend this new research direction and continue the work of [1], proposing an hybrid approach to adapt sandfish-locomotion to lunar environments, in particular to surface vehicles.

3. Locomotion of sandfish animals versus rolling: characteristics and limitations

3.1. Sand-swimming basics

Swimming and movement within granular soils is correlated to many desert animals for survival. For instance, most of the aerial or underwater creatures may be ruled by similar theories adequate to describe interactions in such fluids (e.g. as Navier Stokes equations). However, equivalent force laws for granular drag are not very well set, although several semi-empirical models have been proposed [1, 2]. In particular, the kinetics of sandfish lizard (SL) investigated by Maladen et al. [1], shows the animal reflects an undulatory motion ($R^2 > 0.85$) of a single-period sinusoidal wave:

$$y = A \sin \frac{2\pi}{\lambda}(x + v_w t) \tag{1}$$



(a) (b)

Fig. 1. (a) SLs locomotion principles. RFT method decomposes the animal movement in several differential elements with elemental forces $F_{\perp}$ and $F_{\parallel}$. Notice the wheel's CM always travels towards the right direction forming a sinusoidal-wave type. (b) Wheel parameters for terramechanics definitions. If no side slip is given, $v_y = 0$. Most cases when traversing side slopes or making steering maneuvers, wheels attain $v_y > 0$. In the above study, no side slip is contemplated ($v_y = 0$). Angle θ_m is the angle where the maximal stresses are registered. The wheel moves towards the right with a circumferential velocity $r\,\omega$, with r the wheel radius.

where y is the SL displacement, A the wave amplitude, λ the wavelength, and $v_w = f\,\lambda$ the wave speed defined in terms of the wave frequency f, and x is the traveling direction. Notice, that the wave speed was not equal to speed of the center of mass of the animal. This is because there is an average backward displacement of the granular soil while the animal moves forward [1], inducing a motion resistance and a net slip (in a form very similar to wheels as referred in Section 3.2). This can quantified by a wave efficiency η [1]:

$$\eta = \frac{v_x}{v_w} \tag{2}$$

where v_x is the forward speed of SL, as shown in Fig. 1. Now, resistive force theory (RFT) is typically applied to map the resulting forces during the locomotion of limbless reptiles as snakes and lizards [90], or useful to analyze the undulatory movement of microscopic organisms [91]. RFT encloses empirical formulas evaluating the differential forces acting on a single element of a limited fraction of longitude of the entire animal (Fig. 1 (a)). The elemental tangential force $F_{\parallel}$ and the normal force $F_{\perp}$ are defined in the following form [2]:

$$F_{\parallel} = C_S\, \sin(\arctan(\gamma\, \sin\psi)) \tag{3}$$

$$F_{\perp} = [C_F\, \cos\psi + C_L(1 - \sin\psi)] \tag{4}$$

with γ, C_S, C_F and C_L fitting parameters set according the granular medium [2], while angle ψ is the angle between the axis direction and the local velocity v of the differential element (Fig. 1 (a)). The previous equations are integrated over one wavelength along the traveling direction x:

$$F_x = b \int_0^{\lambda} \left(F_{\perp}\, \sin\alpha - F_{\parallel} \cos\alpha\right)\, \sqrt{1 + \tan^2\alpha}\, dx \tag{5}$$

In Eq. 5, α is the angle formed between the forward direction of the animal and the orientation of the differential element. Next section introduces an analogue theory of RFT applied to rolling in granular media and wheel-soil interactions.

3.2. Wheel kinematics and dynamics

Surface vehicles (or ground vehicles) are those vehicles supported by ground. In specific off-road applications, the group of theories consolidated for understanding and evaluating the capabilities of robot systems (two, three or more wheels) is based in Bekker's models introduced in the early 50's [92]. Even the behavior of off-road rovers represents the results of interactions among the driver, vehicle and environment [93], most of the analytical models are very well described for single wheels since they provide a general idea of the mobility performance of the whole system design. Fig. 1(b) shows the main wheel observables of Bekker's theory. The empirical theory of Terramechanics has been also useful to infer certain terrain properties that allow a soil classification according strength. Let the wheel normal pressure P exerted over the soil sinks the wheel to a height z, then we can express:

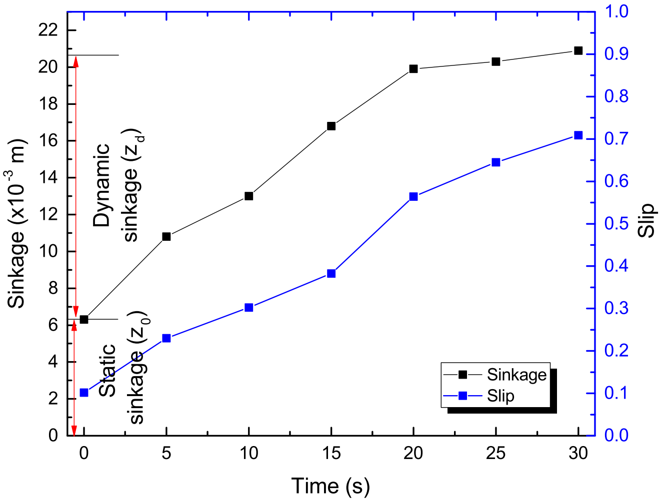


Fig. 2. Laboratory results of the sinkage and slip evolution for the cylindrical wheel prototype of Fig. 4 (a), tested on lunar simulant.

$$P(z) = kz^n \tag{6}$$

where k is the sinkage modulus and n the sinkage exponent, representing intrinsic terrain properties related to it's strength. Now, similarly as SL, the forces and torques acting on the wheel center of mass (CM) are useful to relate the transportability of the rover. Along the contact interface of the wheel with soil (within an angle $\theta_T = \theta_1 + \theta_2$ as shown in Fig. 1), forces can be parametrized as follows:

$$F_x = rb \int_{\theta_2}^{\theta_1} \left[\tau_x(\theta) \cos\theta - \sigma(\theta) \sin\theta\right]\, d\theta \tag{7a}$$

$$F_y = rb \int_{\theta_2}^{\theta_1} \tau_y(\theta) + \int_{\theta_2}^{\theta_1} R_b\, [r - z(\theta)\, \cos(\theta)]\, d\theta \tag{7b}$$

$$F_z = rb \int_{\theta_2}^{\theta_1} \left[\tau_x(\theta) \sin\theta - \sigma(\theta) \cos\theta\right]\, d\theta \tag{7c}$$

where σ_x and τ_x are the normal and tangential stresses generated in the x-direction, R_b is the term employed to evaluate the reaction force generated by bulldozing phenomenon on a side face of the wheel. The function $z(\theta)$ is the sinkage of the wheel. Mapping the forces over the wheel's CM thus require knowledge of multi-axis stresses distributions (τ_x, τ_y and σ of Fig. 1 (b)) and soil constants (k, n), and such

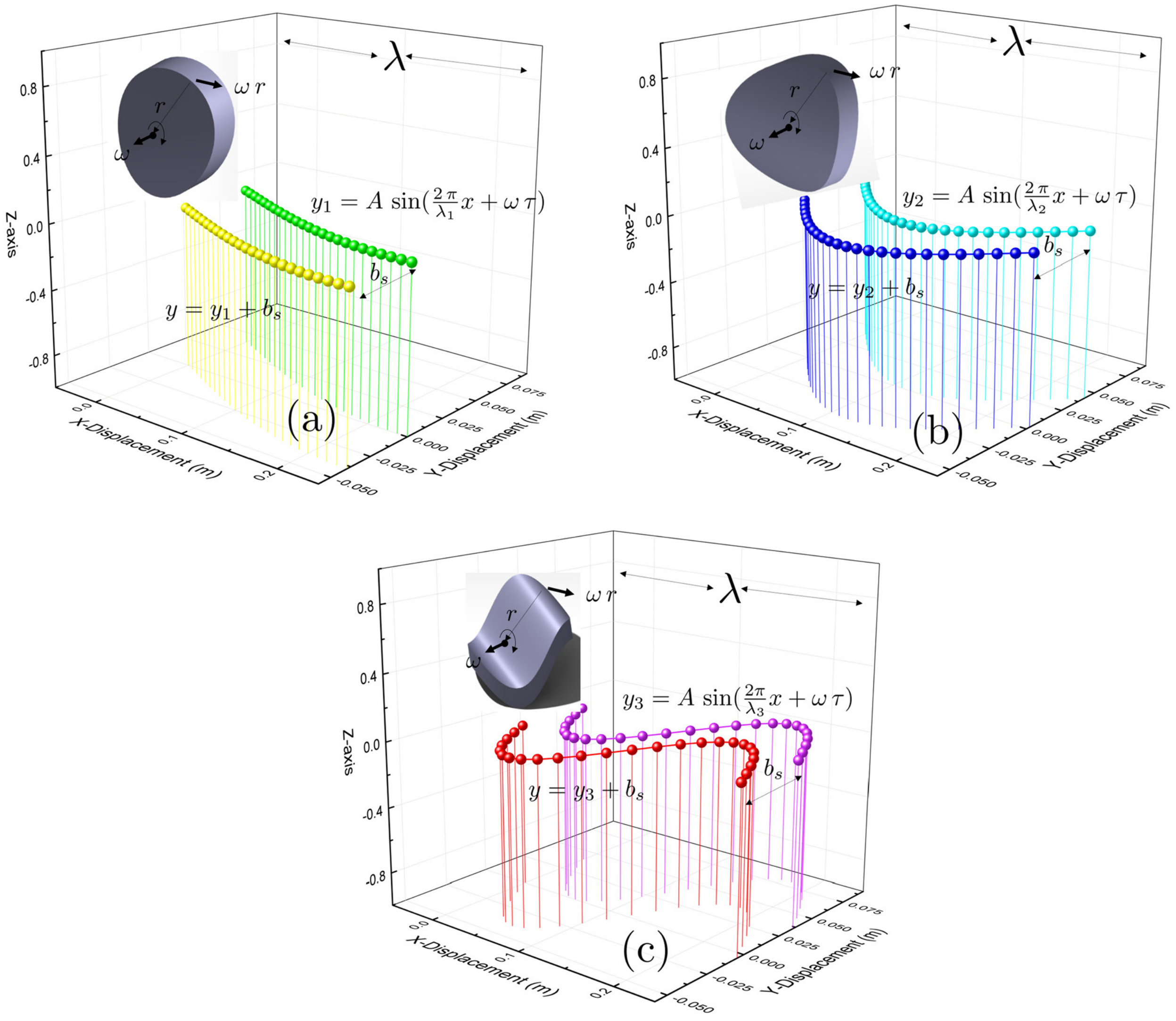


Fig. 3. Bio-inspired wheel designs featuring a constant diameter and different wavelengths: (a) $\lambda_1 = 2\pi/D$, (b) $\lambda_2 = \pi D$, (c) $\lambda_1 = \pi D/2$. The complete design shapes can be reviewed in the Annex (Figs. 4(b)-(d)). The pattern results in conjunction with measurement of other observables allowed us to verify Eqs. 14-18.

detectability is complex for space rovers (i.e. future directions will need to incorporate higher resolution sensors in the wheel perimeter [94]). Regarding the kinematics, notice that while wheel's CM propagates in a given direction, terrain deforms and the wheel sinks, so an equivalent slip is produced. The degree of slip can be defined as the ratio of the longitudinal speed of the CM (in the displacement direction), and the wheel circumferential velocity:

$$s = 1 - \frac{v_x}{r\omega} \tag{8}$$

Finally, it is useful to see from Eqs. 2 and 8, the wave efficiency of sandfish lizards and the slip definitions of terramechanics can be correlated:

$$\eta = 1 - s \tag{9}$$

if the circumferential speed equals the wave speed. It is also interesting to notice that even SL bends and moves forward with almost a constant η (≈ 0.5 in dense granular beds and with very little influence on the volume fraction [1]), the slip associated with wheel locomotion always increases with time, as shown in Fig. 2. Because the wheel sinks while moving forward, the increment of slip provokes wheels to bulldoze soil backwards in a larger rate, making the sinkage also to increase while traveling. Since this phenomenon (slip and sinkage) seems to be always merged, most researchers in the field call this principle “slip-sinkage” [95] or dynamic sinkage, being one of the main performance limitations of wheeled vehicles. Fig. 2 displays the progressive behavior of dynamic sinkage evaluated for a rigid wheel in lunar simulant [96]. Finally, we highlight that the decreasing wheel motility due to slip-sinkage increases the risk of getting stuck: this hazard was the cause of the rover Spirit's permanent immobilization in Mars during May 2009 [70]. On the other hand, as Madlen et al. reported [1, 58, 88], SLs seem to move with constant wavelength and slip, so one interesting exercise is to modify the typical wheel design seeing in Fig. 1 (b) inspired by SL undulatory motion. This is treated in the next section.

4. Bio-inspired design

To deal with wheel locomotion in the high sinkage regime, we propose to use the mobility principles of SLs to improve the performance of rover wheels. The wheel design first shall contemplate a circumference of a constant diameter delimited by a wave-like surface shape, as shown in the Figs. 3 and 4. That way, the speed of a point in the wheel perimeter will be related to the linear motor frequency f, or:

$$v_w = r\,\omega = \pi\,D\,f \tag{10}$$

The previous can be understood from the fact that wheel traces in the ground form a pattern with wavelengths λ, as represented in Fig. 3(a)-(c). Notice, that if $\pi\,D = 2\lambda$, for constants D and f patterns can be defined by distinct wavelengths:

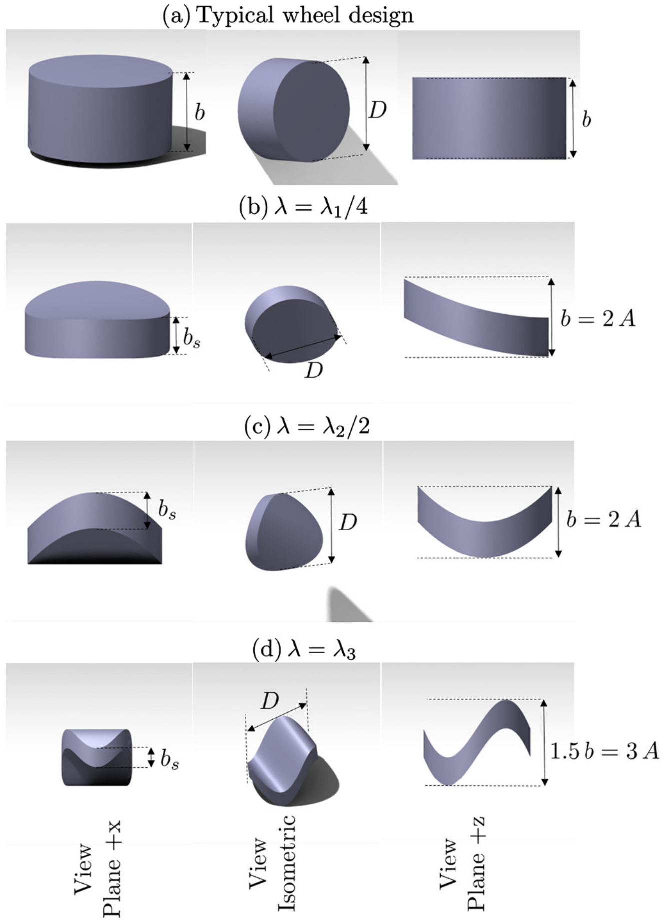


Fig. 4. Wheel designs for varying λ (according Eq. 11 and Fig. 3), for constants $D = 10$ cm and $b = 6$ cm. (a) Represents a typical cylindrical wheel design, while the following models different wavelengths: (b) $\lambda_1 = 2\pi/D$, (b) $\lambda_2 = \pi D$ and (c) $\lambda_1 = \pi D/2$.

$$\lambda = \frac{\pi D}{2} = \left[\frac{\lambda_1}{4}, \frac{\lambda_2}{2}, \lambda_3\right] \tag{11}$$

Now, the traveling velocity can be related to the wavelength and slip by Eqs. 8 and 10:

$$v_x = 2\,(1-s)\,\lambda\, f \tag{12}$$

Eq. 12 shows that under a constant slip, incrementing the wavelength will also increase the wheel velocity, as the diameter will be larger. Fixing the diameter dimensions and the amplitude of the wave pattern, the models depicted in Figs. 3 and 4 are adopted from Eq. 11.

The fact that animals seem to display a constant efficiency η (or slip) while swimming in sand, can be also a useful resource to exploit in exploration missions, since employing wheels with wave-like surfaces can avoid to have the cumulative effect of slip (Fig. 2) while traversing. The analytical formulas to model the dynamics of the proposed wheels are reviewed next.

4.1. Traveling forces

Since no empirical formulas compelling with the wheel design presented here has been proposed in the literature, we shall adapt either RFT or terramechanics-based models to estimate their driving performance parameters. The disadvantage of resistive force theory used in animals relies on the complexity in estimating empirical $F_{\parallel}$ and $F_{\perp}$ constants adjusted to represent each particular experiment. Improved semiempirical models thus are an open challenge in granular media interactions. Because the lack of experimental data, it is also possible to reformulate the problem from a Terramechanics point of view. If L is the work per unit area done to compress the ground at a depth z_o, then:

$$L = \int_0^{z_o} P\,dz = \frac{k\,z_o^{n+1}}{n+1} \tag{13}$$

Now, Bekker [92] observed the total work of traction done by the force R that opposes the movement ($2\,R\,\lambda$ during one revolution), is the same to the work done in compressing the ground at equivalent time ($2\,b_s\,\lambda\,L$), where b_s is the solid width of the wheel. Then we can have:

$$R = b_s\,L = b_s\,\frac{k\,z_o^{n+1}}{n+1} \tag{14}$$

As for the case of Fig. 3, wheels are defined with a solid width line $b_s < b$, where b is the actual width of a plane wheel (see Appendix, Fig. (a)). Thus, for the proposed wheels the movement of resistance R could be lower for a given torque. Since R and the thrusting force are related by Eq. 15 [97, 98]:

$$F_x = H - R \tag{15}$$

individual force terms H and R can be simultaneously determined in similar way as derived in Eq. 7 if knowledge of the normal and tangential stresses in the wheel-soil interaction are given per wheel rotation (e.g. following the instrumentation from [99]). Other approach less complex to solve Eq. 15, is to assume H is the maximum thrust available from Micklethwaite's equation [97]:

$$H = 2\,\lambda\,b_s\,c + W\,\tan\phi \tag{16}$$

with c is the soil cohesion and ϕ the internal friction angle. Notice we will require three soil related constants (k, c and ϕ) towards determining the driving performance of the proposed wheels. Since essentially Eq. 16 derives a constant (maximum) thrust, while Eq. 14 is only applicable to static wheels, an interesting exercise consist on determining the evolution of Eq. 15 during rotation. There are two ways to do that. If the time behavior of the sinkage can be measured (e.g. by visual based estimations [100, 101]), then $R(t)$ will read:

$$R(t) = b_s\,\frac{k\,z\,(t)^{n+1}}{n+1} \tag{17}$$

The empirical formulation of the improved wheel, relates the traveling forces to the time-variation of the dynamic sinkage $z(t)$ (Eq. 17). If this variable cannot be measured, solving for $R(t)$ will require to map the slip instead and use the following equation [103] (or alternatively, any of the eight methods proposed in [102] if more precision is desired):

$$z(t) = z_o\,\frac{1+s}{1-0.5\,s} \tag{18}$$

Finally, we advice the great importance on the new type of wheels presented to avoid high dynamic sinkage and improvement performance regarding traditional cylindrical wheels.

5. Conclusions

With the objective to attract more research on bio-inspired robotics, in this paper we reviewed the most promising concepts for surface or subsurface exploratory robots that have been inspired in animal locomotion. As reported here, bio-inspired explorer robots based on spiders, worms, wood wasps, gophers, snakes or lizards can have enormous potential for future ISRU (In-situ resource utilization) activities, sampling return or asteroid research missions. Besides, we proposed a mobility system that can adapt the motion principles of sandfish for the exploration of planetary surfaces. Hence a new type of robot was presented, consisting on a hybrid wheeled-sandfish design. For assessing their performance, the kinematic and dynamic equations of motion inspired in animal-based empirical models have been reviewed, along the traditional terramechanics approach. We found that analytical models from

RTF are complex to apply for the current bio-inspired design. On the other hand, terramechanics approach is more feasible for deriving the performance of the new wheel, requiring only a few rover observables (as slip and initial sinkage z_o), in addition to three soil-related parameters (k, c and ϕ). Few of the limitations observed are concentrated on defining a correct value for the bulldozing resistance R_b of the improved wheel model. Nevertheless, for cylindrical wheels this can be derived experimentally as function of the wheel sinkage using Hegedus theory [104], even very often terramechanics studies skip this term for assessing the main robot performance [95, 105]. In the latter case, the wheeled robot dynamics can be entirely defined by the equations provided above (Eqs. 7(a) and (c)).

Declarations

Author contribution statement

A.J.R. Lopez-Arreguin: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

S. Montenegro: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

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