Bioinspir. Biomim. 8 (2013) 025003 (9pp) doi:10.1088/1748-3182/8/2/025003

Biomimetics on seed dispersal: survey and insights for space exploration

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Received 19 October 2012
Accepted for publication 20 February 2013
Published 7 May 2013
Online at stacks.iop.org/BB/8/025003

Abstract

Seeds provide the vital genetic link and dispersal agent between successive generations of plants. Without seed dispersal as a means of reproduction, many plants would quickly die out. Because plants lack any sort of mobility and remain in the same spot for their entire lives, they rely on seed dispersal to transport their offspring throughout the environment. This can be accomplished either collectively or individually; in any case as seeds ultimately abdicate their movement, they are at the mercy of environmental factors. Thus, seed dispersal strategies are characterized by robustness, adaptability, intelligence (both behavioral and morphological), and mass and energy efficiency (including the ability to utilize environmental sources of energy available): all qualities that advanced engineering systems aim at in general, and in particular those that need to enable complex endeavors such as space exploration. Plants evolved and adapted their strategy according to their environment, and taken together, they enclose many desirable characteristics that a space mission needs to have. Understanding in detail how plants control the development of seeds, fabricate structural components for their dispersal, build molecular machineries to keep seeds dormant up to the right moment and monitor the environment to release them at the right time could provide several solutions impacting current space mission design practices. It can lead to miniaturization, higher integration and packing efficiency, energy efficiency and higher autonomy and robustness. Consequently, there would appear to be good reasons for considering biomimetic solutions from plant kingdom when designing space missions, especially to other celestial bodies, where solid and liquid surfaces, atmosphere, etc constitute and are obviously parallel with the terrestrial environment where plants evolved. In this paper, we review the current state of biomimetics on seed dispersal to improve space mission design.

(Some figures may appear in colour only in the online journal)

1. Introduction

At first consideration, the notion of borrowing ideas from plant seeds to provide inspiration for the design of artifacts that are designed to function away from the Earth might seem a strange one. However, space exploration places unique requirements upon engineering which actually increase the desirability of capturing the characteristics of biological organisms in general, and of plant seeds in particular.

To understand why this should be so, it is worth considering some typical features of a space mission: (i) the space (and extraterrestrial) environment is harsh (extreme temperature, radiation etc) implying that the spacecraft and its materials need to be designed for these conditions; (ii) any spacecraft that leaves our planet needs to survive the launch phase, characterized by high accelerations and powerful vibrations. Therefore, the spacecraft has to be materially and structurally robust, which in turn implies greater mass. (iii) Space missions are mass-constrained and volume-constrained due to the launch phase, so mass efficiency of the material and packaging efficiency of the whole structure are very desirable characteristics. These requirements are essentially opposites: they call for lightweight materials that satisfy structural and packaging requirements whilst being resistant to extreme temperature, radiative and vibration loads.

Similarly, plants need to carefully define the relationship between fruit mass, dispersal structure size and morphology, and doing so they have to account the resources available and their environment. They have to build hard shells to protect the small embryo from external agents, but this small payload has also to comply with the requirements of the dispersal methods: drifted seeds have to be buoyant, resist the corrosion due to sea water and guarantee the survival of the embryo for long periods; and in wind dispersal, the plant has to carefully scale the size of the 'pappus' (the hairy parachute attached to the seeds) with respect to the fruit mass [1]; therefore, the plant investment for the dispersal unit is designed to perform optimally in the range of loads the plant decided to invest for the seeds [2].

In space missions, the environment is always unknown to some extent, and this imposes a degree of dynamic variability that is very hard to be explicitly accounted for in the design phase. Consequently, all space missions must incorporate a degree of autonomy to allow them to compensate for and adapt to environmental changes. There are also long communication delays between the ground station and the spacecraft, mainly due to the enormous distances involved [3]. Furthermore, knowledge of the environment decreases with distance, and the communication delays prohibit effective responsive control of the spacecraft from the ground. Therefore, spacecraft have sometimes to perform mission-critical activities without any supervision having an active goal-directed behavior. Similarly, plants prepare for changing environmental conditions in the best possible way. They develop 'dormant' seeds and design robust ways to disperse them. Dormancy is a state of reduced metabolism that enables the seed to withstand harsh environmental conditions for extended periods [4]. Thanks to dormancy, seeds that mature in autumn have no problem in surviving winter and when they encounter more pleasant external conditions in spring, they reboot the metabolism and start germinating. The complex mechanisms that lead to dormancy can also give many advantages in the population dynamics: in regions prone to wildfire for example, fire tolerant species are frequently encountered. In these species, fire is able to break down the hard seed coat and trigger germination, so that they will germinate immediately after fire on the ashes of the previous vegetation [5]. This is a strong similitude with the hibernation phases that some space missions need to consider: Rosetta, for example, is a robotic spacecraft of the European Space Agency on a mission to study the comet 67P/Churyumov-Gerasimenko [6]. The spacecraft will enter a slow orbit around the comet and gradually slow down in preparation for releasing a lander in May 2014. In June 2011, the spacecraft was placed into a deep-space hibernation state due to its enormous distance from the Sun and the weakness of the sunlight falling on its solar panels, which cannot produce enough electricity to fully power the probe.

The paper is structured as follow. In section 2, we describe the diverse methods that seeds use to disperse into the environment and in section 3 we enumerate some of the technologies that were inspired by them, or that could potentially be inspired by them and used in future space missions.

2. Seed dispersal methods

There are many reasons why seed dispersal is integral to the survival of plant species.

- seeds provide the vital genetic link and dispersal agents between successive generations, traveling in time;
- plants lack any sort of mobility and they rely on seed dispersal to conquer new habitats, traveling in space;
- to find favorable environments without the danger of interbreeding in local habitats near the parent plant;
- to reduce competition with other seeds from the same plant;
- and finally, to reduce mortality due to predators or diseases that might be present in the area.

Therefore, it is reasonable to think that the strategies available now are the result of years of strong natural selection, and even if at a quick glance they may not seem optimal for their specific tasks, studying them in detail reveals an incredible level of perfection.

The great variety of dispersal-aiding morphologies has attracted the attention of naturalists since Aristotle (384–322 BC) [18]. The most commonly used classification system of dispersal is based on the agent or vector of dispersal. The principal agents of dispersal are either abiotic (wind and water) or biotic (animals and the plant itself) [7], and seeds can take advantage of one or more of these strategies using the most abundant forms of energy available. To do so, they evolve specific shapes, structures, colors, flavors and smells to move throughout the environment . Some examples of the common seed dispersal strategies are listed in table 1, and include the dispersal agent involved and a botanical example. There are juicy seeds adapted to attract animals [7–9], buoyant seeds that float thousands of miles [10, 11], wings and parachutes capable of aerial transport [12, 13] and ballistic fruits that can shot seeds several meters away [15].

In the following subsections, the main seed dispersal methods are described in more detail.

2.1. Animal dispersal

Animals of all sorts and sizes help plants to disperse their seeds. The method they use depends on the type of seed. Some plants have attractive seeds so that animals and birds are encouraged to act as seed carriers. Ants carry seeds into their nests, eat the tasty outer covering and leave the seeds to grow safely underground. As well as eating them, some animals collect the fruits or seeds and bury them to eat later, but forget about them and the seeds germinate in their new location [8]. Sometimes, the plants make use of animals to carry their seeds without giving them any reward. Many plants produce fruits or individual seeds covered in hooks or spines which attach the seed to the animals' fur or feathers. These hitchhikers are then carried to a sufficient distance from the parent plant to give them space to grow. Eventually, the seed may fall off, or be rubbed off by the animal.

Table 1. Seed dispersal methods.

Dispersal agent	Type of dispersal	Sub-category	Sample specie	Reference
Animals	Edible	Juicy fruits	*Prunus avium L.*	[7]
	Hitchhikers	Take away	*Quercus serrata*	[8]
			Archtium spp.	[9]
Water	Buoyancy		*Cocus nucifera L.*	[10]
	Unwettability		*Arctotheca calendula*	[11]
Wind	Winged	Spinning	*Acer spp.*	[12]
		Gliding	*Alsomitra macrocarpa*	[12]
		Rocking	*Lilium longiflorum*	[12]
	Parachuted		*Taraxacum officinale*	[13]
	Other means	Tumbleweed	*Babtisia spp.*	[14]
Self-dispersal	Ballistic		*Hura crepitans*	[15]
	Shaker		*Papaver somniferum L.*	[16]
	Hygroscopic		*Erodium cicutarium L.*	[17]

2.2. Water dispersal

Plants that grow close to the water evolved methods to disperse the seeds using river flow and sea currents. They produce positively buoyant seeds or fruits, which, thanks to their hard shells, can survive and stay buoyant for several months. Coconut, for example, is highly water resistant and disperses significant distances via marine currents [19]. In some cases, the seeds evolved special structures, such as *Sacoglottis amazonica* which has air-filled cavities to reduce its specific weight [20]. Also, the outer surface of these seeds is properly modified: any surface in humid environments would be normally subjected to fouling (e.g. barnacles, and algae can colonize the surface), but some seeds prevent the development of such unwanted organisms, remaining clean and able to survive longer [21].

2.3. Wind and air dispersal

A big family of seed dispersal methods exploits the wind. Flying seeds can be generally found in dry climates, where they benefit from seasonal winds. They are mainly produced by tall trees to take advantage of the height of their release [9]. Flying seeds can have small soft hairy parachutes using the drag force to slow the rate of descent, or membranous wings, to generate lift. Winged seeds also have different flight dynamics: some of them glide, some rock down and some can even spin like helicopters. Many studies have been conducted in the past, and detailed description of their flight performances is available [22, 12].

2.3.1. Spinning flight. In the case of spinning seeds, the rate of descent, spinning rate, pitch angle and other parameters were carefully characterized given their morphological properties (mass, wing area, wing loading, position of center of mass). The goal was to understand the aerodynamics and assess the optimal performance of their auto-rotational flights, and it has been demonstrated that they are not far from being optimal rotors. The single blade of samara seeds such as *Acer spp.* may be the one which performs best [22]. In its rotary descent, the seed decreases the acceleration caused by gravity and reaches a self-stabilized descent. In this flight regime, all forces and torques are balanced and thus only uniform rotations and flights are possible. [22]. A comprehensive study on samara's flight has been recently published [23], revealing that its unexpected high lift is due to the airfoil and the formation of a stable leading-edge vortex. The same principle is responsible for the high lift generated by hovering insects, and represents a convergent aerodynamic solution in the evolution of plants and animals to increase the time they can remain in the air.

2.3.2. Gliding flight. A wide range of seeds perform a gliding flight. *Dioscorea japonica* and *Betula platyphylla* are only two examples. Usually the flight path of gliding seeds is quite steep, from 35 ° to 90 °. In this range, the seeds maximize the lift-to-drag ratio (and consecutively the minimum rate of descent) as shown by wind tunnel tests [12]. The gliding flight of seeds is rarely stable, and it can result in a spiral or rocking path due to oscillation caused by nonlinear behavior of the flow. The big seed of *Alsomitra macrocarpa* represents an exception, and it is described as an extremely high-performance glider. It is a liana-plant, bearing the bell shaped fruits (about 30 cm diameter in size) at the top of the forest canopy, packed with large numbers of seeds. Seeds have papery wings that can span some 13 cm, and are able to perform a gentle gliding. Its average angle of attack is 12 °, and at this value the lift-to-drag ratio is maximum, resulting in the minimum rate of descent [24]. Many gliding seeds, such as Alsomitra, are found in tropical forests where the atmosphere is calm and they can benefit from updrafts rather than gusts of wind.

2.3.3. Parachuted flight. The hair-like plumes that constitute the parachute of many seeds can be arranged in a sphere, a semi-sphere or a circular cone. In calm atmosphere, these seeds can make a vertical descent flight, reaching equilibrium when the aerodynamic drag and the weight of the seed are equal. Many studies have been conducted in the past, plumes have been modeled and their rate of descent has been described [13, 2, 25]. Parachuted seeds are designed to travel passively with the wind and their dispersal potential is proportional to their settling velocity. The shape of the plume can dramatically affect this parameter, and some studies reported that the cone-shaped configuration is the most effective [25]. A deeper study of such structures and their aerodynamics would indeed give new insights to engineers,

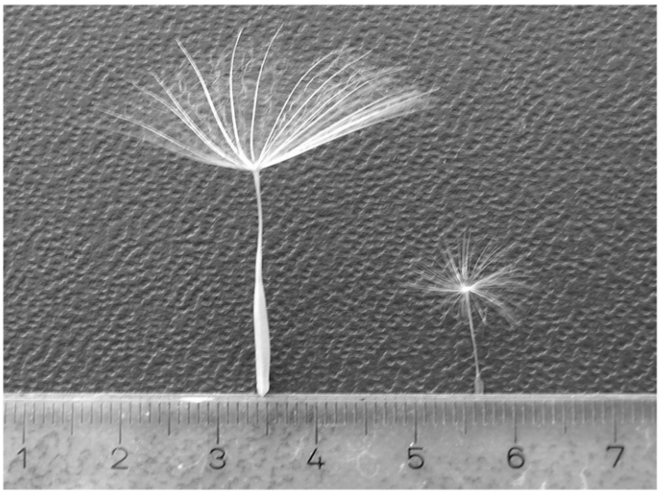

Figure 1. *Tragopogon dubious* (left) and *Taraxacum officinalis* (right); an example of how nature scaled up a parachute.

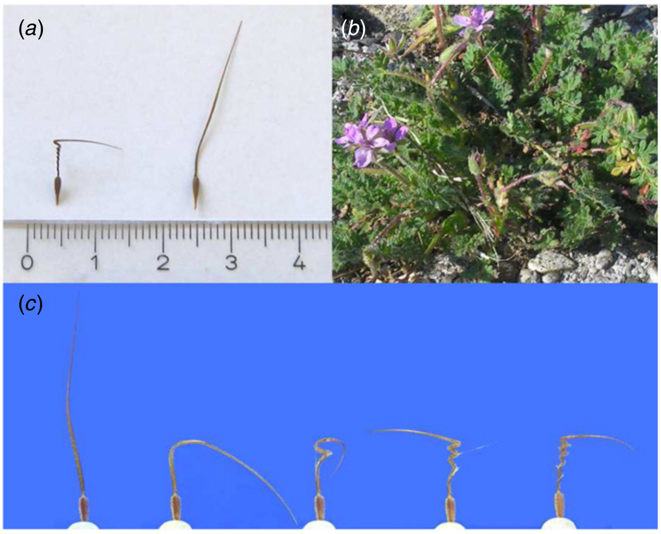

Figure 2. *Erodium cicutarium*: (*a*) dry seed on the left, wet seed on the right; (*b*) morphology of the plant; (*c*) snapshots of a drying cycle.

and could bring a new stream of designs for lighter parachutes. But the scale up phase is quite delicate, and what has been conceived at a given size does not work the same at a different scale, and challenging bio-mechanical problems and different aerodynamic characteristics can arise. *Taraxacum officinalis* and *Tragopogon dubious* offer a good subject of study. They belong to the same botanical family—Asteraceae—and share the same means to disperse their seeds, both having a stalked cone-shaped parachute attached to the seed (figure 1). Even if the shape is very similar, *Tragopogon dubius* is almost three times bigger and it builds its parachute with a fine texture of fibers hierarchically structured, and radially arranged from the center [13].

2.3.4. Tumbleweed. Tumbleweed is the last wind-dispersal strategy presented here, and it occurs when a whole or a part of the plant disengages from the root apparatus and starts being blown by the wind [7]. It has been reported for a variety of plant species, roughly spherical in shape, that are native of prairies, deserts or other open areas subjected to strong winds [14]. While tumbling with the wind, thousands of seeds are released from the dried fruits over wide areas. A few examples are the Russian thistle *Salsola kali*, the winged pigweed *Cycloloma atriplicifolium* and Florida sandhill *Baptisia lanceolata*.

2.4. Self-dispersal

Some plants disperse their offspring by themselves, and also in this case the strategies are many, and worthy of mention. They can use some external sources of energy to bend their stalks so that the seeds spill out of the seed pod, falling a little away from the parent plant, such as poppy seeds (*Papaver spp.* [16]). Sometimes they rely on hygroscopic structures that change their configuration according to the external humidity, releasing the seeds from their pod, or propelling them into the soil. Hygroscopic movements in plants are quite common and are possible thanks to the particular structure of the cell wall. The cell wall is a composite material consisting of crystalline cellulose microfibrils embedded in a soft matrix (polysaccharides, aromatic compounds and structural proteins). Whereas the matrix can absorb water, the crystalline cellulose structure cannot. Therefore, the direction of the contraction of a drying tissue reflects the cellulose microfibril orientation. [26]. Finally, plants can have ballistic dispersal, by using the explosive opening of the fruits or the springing of levers to shot the seeds away.

From a biomimetic point of view, the more interesting self-dispersal methods are the last two categories: ballistic and hygroscopic dispersal. Hygroscopic tissues play many different functions: they can be responsible for the elastic contractions used in ballistic dispersal, but also could simply bias the right time of dispersal. In pine cones, a decrease in the relative humidity causes a gradual opening of the scales, from which, in a dry climate, many winged seeds are released. Wild wheat and *Erodium cicutarium* seeds are equipped with hygroscopic dispersal units that are able to propel the seeds on and into the ground [27, 17]. The arrangement of the fibers causes bending of the awns with changes in humidity. And whereas a single awn of *Erodium* coils and uncoils, the two awns of wild wheat open and close, resembling the swimming stroke of frog legs. These movements are reversible; thus, the humidity cycle causes a periodic movement of the awns. This suggests that the awns—made up of dead tissue—act as a motor, fueled by the daily humidity cycle. In particular, the fruits of *Erodium cicutarium L.* consist of five seeds joined together and forming a spine like structure. As the fruits dry, the seeds increase their tension, and the stresses developed in the structure cause them to separate abruptly and fly away up to half-a-meter away [17]. Once on the ground they show a very peculiar borrowing behavior, possible thanks to movements achieved by changes of external humidity (figure 2). The humidity changes cause the awns to unwind straight when wet, and rewind back to their helical shape when dry. The resulting motor action moves the seed across the surface, eventually lodging it into a crevice and causing it to bury itself into the ground.

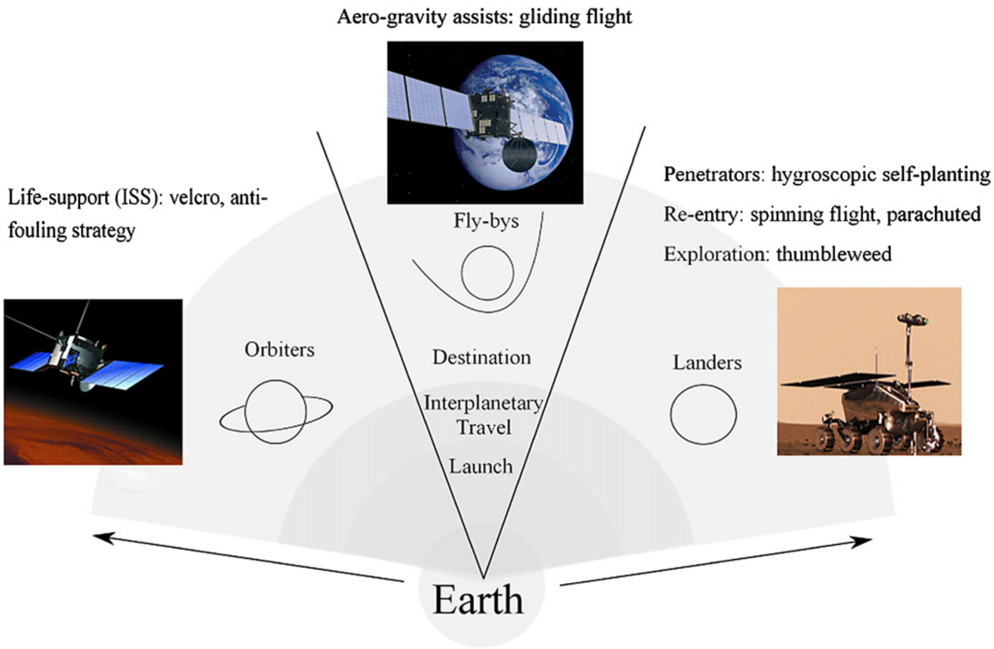

Figure 3. Different types of space missions and biomimetic ideas that could help (images from left to right: Mars Express, Rosetta and Exo-Mars, Credit: ESA).

In the case of ballistic dispersal, seeds are ejected from the fruit by the elastic contraction of the tissues so that seeds are flung away from the parent plant. Seed projection angle, height, drag and initial seed velocity are the consequences of a combination of physical features of the plant, and many examples can be found in nature. The sandbox tree (*Hura crepitans*) is one of the most remarkable examples. It can shot the seeds with an initial velocity of 70 m s^{-1} thanks to the morphology of the launch apparatus [15]. During the maturation of the seeds, the fruit begins to dry, increasing the stresses inside the structure that finally cause the explosive release.

3. Biomimetic solutions inspired by seed dispersal methods

'Space missions' is a rather generic term to indicate systems designed to go beyond our atmosphere. Going into more detail, one immediately realizes that space missions are very diverse in objectives, morphology, duration, requirements and cost. A complete taxonomy is beyond the scope of this review paper, but one may want, at this point, to attempt a coarse classification useful for the purpose of looking into different seed-inspired technological solutions that have been proposed so far. In figure 3, we have depicted a generic space mission as made by a launch phase, an interplanetary travel phase and a destination phase (some missions may actually also have a return phase, which we have not included in our simplified schema). Missions can be further divided into orbiters, fly-by probes or landers according to whether they are captured into the final destination gravitational field or not and whether a descent into the destination is planned. Missions such as the International Space Station (ISS), telecommunication satellites, Earth observation satellites or most space telescopes are thus orbiters, while the early solar system exploration, performed by probes such as Voyager and Pioneer, made extensive use of fly-by encounters. Landers (including probes crashing on the planet surface) are not only, scientifically, the most interesting exploration missions, but are also the most challenging from an engineering point of view. As hinted by figure 3, these types of space missions have been the objective of quite a number of proposals to use technologies rooted in the biomimetics of seeds. In the following sections, we will introduce in more detail a few solutions, used, proposed or even just conceptualized to aid a space mission.

3.1. Hitchhiker seeds and Velcro

Maybe one of the most famous and celebrated examples of solutions bio-inspired by the plant kingdom is Velcro. It was invented in 1948 by the Swiss electrical engineer George de Mestral who patented it in 1955 [28]. De Mestral based his invention upon observation of seed burrs sticking to the hair on his dog. These hook-and-loop fasteners consist of two components: the first one features tiny hooks, resembling burdock (*Arctium spp.*), and the second one features even smaller and 'hairier' loops, functioning as the fur of animals. When the two faces are pressed together, the hooks catch in the loops and the two pieces fasten temporarily. Velcro fasteners are widely used in aerospace applications: they were first introduced by NASA, and are now commonly used to comply with many everyday life tasks, such as attaching food pouches to walls and note pads to astronauts' legs, as well as in other more demanding tasks such as the extra-vehicular activities. The advantages of velcro are many: it is a dry adhesive, and it does not require any sort of glue or chemical to work; it does not need a perfect coupling between the two sides; it can be quickly attached and detached; it can stand many loads given they are not applied with high acceleration, and it requires very little maintenance.

3.2. Buoyant seeds—antifouling strategy

Many biological surfaces with self-cleaning and anti-microbial properties have already been translated into interesting technologies. Lotusan® is an exterior coating to keep surfaces dirt-free without chemical detergents or expending energy, and it uses the same micro-structural principles found in lotus leaves and described as 'the lotus effect' [29], and Sharklet is a microscopic pattern that mimics shark skin, creating a surface upon which bacteria exhibit reduced growth [30]. The ongoing study of the anti-fouling principles of buoyant seeds [21] could turn out to be equally successful. Self-cleaning, anti-fouling, anti-microbial surfaces can have many beneficial applications in space. During the past long-term manned missions, more than 100 species of microorganisms (mainly bacteria and fungi) have been identified on surfaces of materials. Some were potentially pathogenic and might threaten human habitation and some caused a degradation of materials resulting in failures and disruptions in the functioning of equipment and hardware. Spacecrafts have a microclimate which is optimal for microorganism growth: the atmospheric fluid tends to condense on the internal surfaces, together with chemical contaminants and human metabolic products that are in the air. Russian long-term missions on board the space station MIR have demonstrated that uncontrolled interactions of these microorganisms with materials ultimately lead to the appearance of technological and medical risks, influencing safety and reliability [31]. Therefore, countermeasures focused on microbial contamination management are now essential for the safety of the ISS and the next long-term manned missions where risks associated with extended stays will be even greater [32]. Therefore, self-cleaning, anti-fouling paints could be used for the coating of sensible materials on board spacecraft during manned missions, helping in preventing the development of contaminants, and on the ground, to improve the cleanliness of the facilities in which spacecrafts are built and tested before launch.

3.3. Spinning flight

Spinning seeds inspired many types of powered monocopters, such as the small unmanned vehicles SAMARAI, resembling the maple seed. In this small hovering monocopter (less than 15 cm in size), the active control of the feathering angle is able to generate a lateral motion [33]. The self-stabilized descent of spinning seeds has also been studied for passive landing. Autorotation is well known in the aeronautical field, and it is already used to perform unpowered landings in the event of engine failures of helicopters. Similar concepts can be applied for the entry phase of a spacecraft into an extraterrestrial atmosphere. The current technologies used for the Mars Exploration Rovers and Mars-Pathfinder consisted of a combination of parachute descent, thruster control and airbag assisted landing to deploy the mobile payloads on the surface [34]. Autorotation could represent a valid alternative to parachutes. During autorotation, in fact, the rotor is not driven by an engine, but by the upward air-flow while the craft is descending. This can provide as much lift, or equivalent drag, as a circular parachute of the same diameter, and the

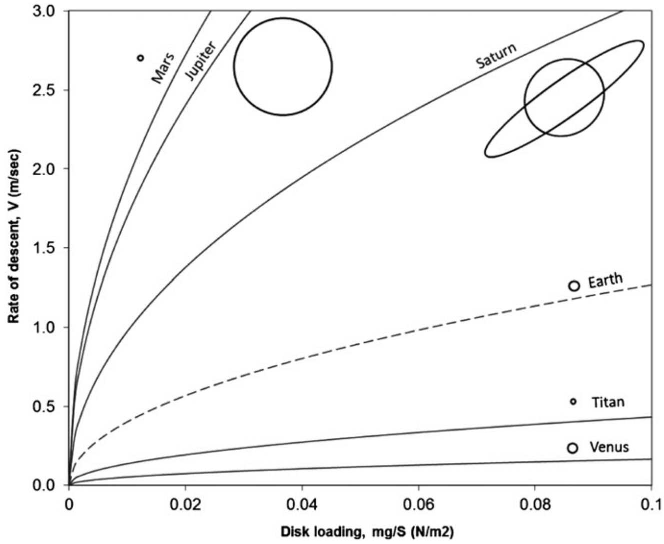

Figure 4. Rate of descent (V) on Mars, Jupiter, Saturn, Earth, Titan and Venus.

moving rotor can then be used as a control device to perform manoeuvres during the last stage of the descent. The early concept of using autorotation to slow the descent in the Martian atmosphere was introduced in 1968 [35], and some proof of concept was done [36]. Autorotation revealed to have some advantages with respect to the parachute, in particular, it has major capabilities in terms of soft and precision landing, hazard avoidance and payload mass [36].

A preliminary computation can be done on what the rate of descent of autorotating seeds can be on different planets by using equation (1) from Azuma and Yasuda [22]. The equation was obtained by applying the momentum theory to calculate the minimum rate of descent in an optimal state of operation (S represent the disc of rotation) and we used average atmosphere density (ρ) and gravity (g) that characterize the different planets, and plotted them on the graph in figure 4. Considering a payload of 1 kg, and 1 m s^{-1} as desirable final velocity, the obtained disc loading radius (and consequently the length of the wing) may be as follows: 2.3 m for Earth, 10 m for Mars, 0.77 m for Titan and 0.29 m for Venus:

$$V = \sqrt{(2/\rho)(mg/S)}. \tag{1}$$

3.4. Gliding

The gliding seed of *Alsomitra macrocarpa* is said to have been the inspiration in 1904 for the wing planform designed by Igo Etrich, which was first flown as a kite, and then as a glider, the craft proved to be a milestone in aviation history, gliding for about 900 m [37, 38].

Gliding flights could be used in aero-gravity assists (AGA): a modification of the proven technique of gravity assist. In general, gravity assists can be used to reduce the launch energy requirements for a given mission or to increase the science return by enabling more planetary, satellite or asteroid encounters. The gravity-assist technique is limited, however, by the turn angle which can be effected by a fly-by body. This angle depends on the size and mass of the planet and the magnitude of the relative velocity. One method of circumventing this angle limitation is to use AGA: the spacecraft approaches the body, dips into the atmosphere and using aerodynamic lift can curve the trajectory. This enables the spacecraft to deflect through a larger angle, resulting in a higher delta-v (change in velocity). This in turn allows a shorter travel time, a larger payload fraction of the spacecraft, or a smaller spacecraft for a given payload [39]. AGA are so far theoretical and have not yet been used; however, the study of the aerodynamic properties of gliding seeds could give some inspiration to advanced designs of spacecraft performing AGA, if some dynamical analogy is first established.

3.5. Parachuted seeds

A current project of the European Space Agency is looking at the arrangement of the fibers of the parachuted seed of *Tragopogon dubius*, and how this contributes to the aerodynamic properties of the seed [40]. The study of this small parachute could reveal some interesting principles that determine its incredibly efficient dispersal method. Small payloads could be deployed in an extraterrestrial atmosphere, and traveling with the wind currents could perform multiple measures over large areas of interesting atmospheric properties to send back to Earth. This could be applied on Venus, where atmospheric dynamics still remain elusive. Recent knowledge reveals that heating and cooling rates, local winds and other atmospheric parameters are very inhomogeneous and difficult to model. The need to investigate this behavior favors the use of a large number of small probes to sample different parts of the weather at the same time. A swarm of probes could then be used to understand the structure and variability of the climate system on the planet. The option to deliver a smaller amount of bigger probes carrying more sophisticated instruments is less recommendable due to the high loss of coverage that would ensue. Given the mass constraints of such small probes, in a study from Cody Technology Park and University of Oxford, scientists selected only three key basic measurements (temperature, pressure and light level), and using the state of the art miniaturized sensors, the overall mass of each single probe would be within 12 g [41] with an average drift speed of 2 to 5 m s^{-1}. With the due difference and the scaling factors, these numbers are compatible with the performance of seeds and therefore represent a good sample to design the probes.

3.6. Tumbleweed

The tumbleweed dispersal strategy attracted the attention of the Jet Propulsion Laboratory (JPL) of NASA, inspiring a new concept of robotic surface mobility [42]. The spherical shape allows the robot to face all kinds of obstacles and operating surfaces, since a rolling ball naturally follows the path of least resistance. These advantages include good stability, low rolling resistance, and most importantly, the robot can resume stability even after collision, making it suitable in unfriendly environments. JPL concept of the tumbleweed-rover was a wind-blown inflated ball, cheap and fast moving in the windy harsh environments of Earth or outer planets [42]. In the proposed operational scenario, the tumbleweed rover deflates to stop at areas of scientific interest, takes measurements, relays the data back to Earth and re-inflates to continue on its journey. A scale model of it has been successfully deployed in Greenland, where the rover tumbled over 130 km in less than 48 h while sending back data [42]. Other spherical robots with stirring and omnidirectional rolling ability were stimulated by this device [43, 44]: for example, a turbine-shaped tumbleweed was designed to improve the response to the wind load, and equipped with a lever ballast to stabilize the motion around the rolling axis [45].

Table 2. Physical and mechanical properties of lunar soil (modified by [46].)

Lunar soil sample	Average particle size (mm)	Bulk density (g cm^{-3})	Void ratio
Apollo 11	0.098	1.36	1.21
Apollo 12	0.118	1.15	–
Apollo 14	0.138	0.89	2.26
Apollo 15	0.061	1.1	1.94
Luna 16	0.085	1.115	1.69
Luna 20	0.077	1.040	1.88

3.7. Hygroscopic self-planting

In the 1980s, some experiments were done to provide information on the performance of the self-burial seed of *Erodium cicutarium* [17], and an extensive study of its fibers and of the coiling of the tail was done more recently [47, 48]. Studying the dynamics of this self-planting technique could lead to a new method for drilling. The main characteristics that governs soil physical and mechanical properties are the granulometric composition (i.e. size and shape of the particles), the degree of packing, as estimated by the void ratio (i.e. ratio of void volume to solid volume), and the bulk density (i.e. ratio of the mass to total volume). Scientists have not agreed yet to what extent each of them affects the self-burial performance of the seeds, but there are pieces of evidence proving that surface irregularities are crucial for the self-burial behavior of the seed [17]. Given the small size and weight of the seed, it is also reasonable to think that the system does not need high axial force for the penetration, applying a motion that requires no additional steady coupling with the surface. A system with these characteristics could be very useful in space [49], providing a different solution to the set of unconventional drills developed to address this purpose [50].

Mars, the Moon and many other solar system objects (e.g. asteroids) are covered by a layer of granular material. Their composition is highly variable and depends on the geological processes which led to their formation. As far as the Moon regolith is concerned, a large number of studies on the soil properties were performed by missions that returned soil samples to Earth. In table 2, some soil characteristics are given for the samples collected by the missions Apollo 11, 12, 14, 15 and Luna 16, 20 modified by [46]. More studies are certainly needed to address the specific performance of the seeds in soils that resemble more closely the properties of Lunar regolith,

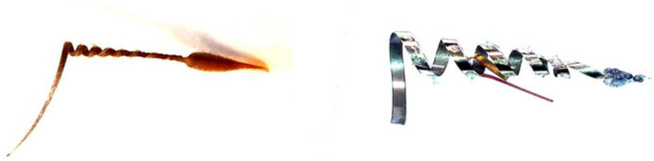

Figure 5. A possible and preliminary engineering of the *Erodium cicutarium* (left) making use of a bi-metal strip (right, out-of scale) (unpublished image from the Advanced Concepts Team: prototype by Johannes Simon).

but it is reasonable to think that under such conditions, the seeds would be able to establish successfully. Rubble pile asteroids could be another interesting target of a penetrator that is exploiting the seed behavior. These kinds of asteroids are weak aggregates of large and small components, held together by gravity rather than material strength. The asteroid Itokawa was the target of the Japanese Hayabusa mission that returned soil samples to Earth. Mineralogical analysis of the particles indicates that they consist mainly of coarse (10 to 50 mm in diameter) crystalline silicates [51], confirming once more that these properties are compatible with the habitats of the seeds and could be a reasonable target of further analysis.

Understanding the contribution of gravity to the performance is also fundamental to confirm the potential application to asteroids and low gravity planetary bodies, and certainly more specific experiments are needed to address this issue [49].

From a technological point of view, the hygroscopic mechanisms of the seed would hardly be replicated in space, where there is little atmosphere if any. Therefore, the coiling–uncoiling movement could be replicated passively by smart memory alloys or bi-metals (figure 5), exploiting the extreme differences in temperature experienced in space between day and night. For example, on Eros, one of the largest near Earth asteroids, the daytime temperature is around -100° C and during night about -150° C (rotation period is around 5.27 h), while on the Moon typical daytime and nighttime temperatures are -200 and 100° C, respectively.

The Erodium-inspired space probes could therefore facilitate the sub-surface exploration of planets. For example, sensors could self-bury to give information related to the geology and seismology of the planet, the temperature or simply dig themselves in to find shelter from the space environment.

4. Conclusion

Space exploration presents many challenges: from extremes of temperature, vacuum, shock and gravity to limitations on power and communication, from the intricate complexity of systems engineering to requirements for reliability, robustness and autonomy. Facing this complexity with currently established engineering practices and solutions can be very expensive, and there is a strong need to find simpler ways to approach this complexity. Nature can help in this process, presenting many examples from which it is possible to extract very successful working principles. In this review we presented a few solutions, used, proposed or just conceptualized to problems typical of some space missions. The tumbleweed rover designed by NASA traveled 130 km in less than 48 h in Greenland, whereas velcro is extensively used in many of the everyday tasks on the International Space Station. Self-cleaning, anti-fouling, anti-microbial surfaces could find applications to the microbial contamination management on board spacecraft or inside the clean rooms used to built and test spacecraft. The self-burial behavior of Erodium could contribute in the sub-surface exploration of planetary bodies, and the deployment of parachuted probes could enhance the understanding of extraterrestrial atmospheres.

Understanding in detail how plants control seed dispersal can therefore give some advantages in improving space exploration. Plants have already found what works to disseminate on Earth, and they exhibit many examples of robust design and specialized functionality that are worthy of study.

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