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Biologically inspired solutions for robotic surface mobility

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1 Abstract

The application of biomimetic locomotion to the Martian surface offers the possibility of increased robustness and failure tolerance. This study will search for new innovations from nature and to develop a novel system to provide robust and efficient locomotion system to be used for exploring of foreign planets. When considering novel systems, one should consider locomotion and power generation methods that would utilize local power generation resources like wind or heat. Some of already consumed energy can be re-gained with novel solutions during atmospheric descent or rolling down the dynes, as for an example.

The robotic tumbleweed would imitate natural tumbleweed and would travel along Martian surface driven by the wind or by it's internal motor, or rolling down the slopes. The robotic tumbleweed might also have a possibility to jump or being pushed over some obstacles.

Identification and development of promising novel techniques of locomotion in planetary environments is a priority. This study will involve the identification and conceptual development of one or more innovative concepts for planetary surface locomotion. Several concepts are presented and evaluated. Considering nature of the study, although evaluation reveals some concepts propably not adequate, these are not removed from the report, but are left here for the interest and further inspiration of the reader.

2 Introduction

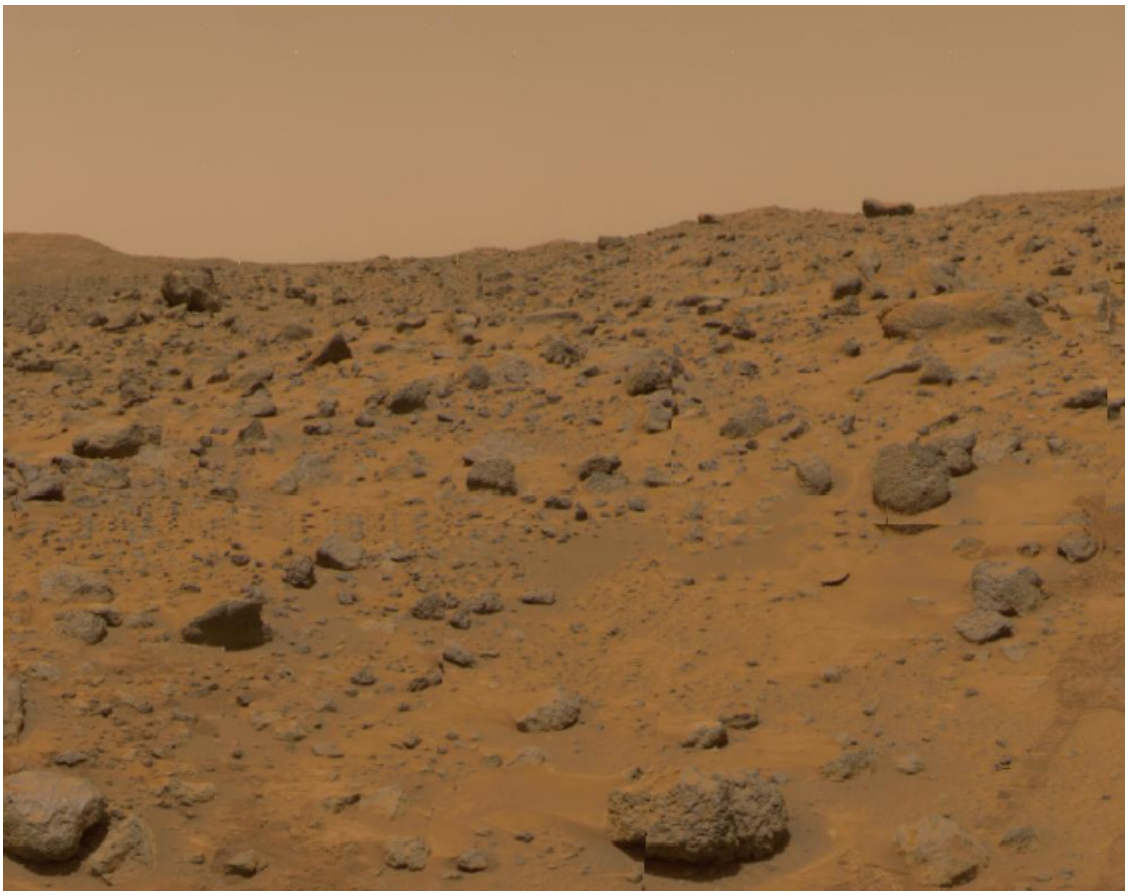
The planetary objects to be explored in future have surfaces of varying properties. Some planets are covered with fluid; some moons or asteroids have icy or snowy cover. When considering scientific results that would be gained through moving around and exploring planet surface, objects with sandy or rocky surface seem the most interesting at the moment, although swimming and diving -or even flying- robots might be very interesting subjects on planets covered by fluid or a gaseous atmosphere. Even these rocky planetary objects have a much varying nature; some are hot, some are cold, some have atmosphere, some do not, some have volcanic activity and some do not, some have magnetosphere and some do not, etc. etc.

Requirements on mobility are directly derived from the scientific requirements. The required distance between measurement points drives the design of the locomotion system and, in particular, its speed. This latter, in turn, together with the minimum number of measurements, drives the minimum time of presence on the surface needed to accomplish the scientific goal. According to [RD 2] minimum distance specified is 0.5 km, and maximum is 2 km, and number of samples is 10, which makes minimum travel distance 5 km, in case the system does not return to the lander at all, but acquires and sends the data autonomously.

Basic problematic is shared among all the rocky/sandy planets: we do not exactly know what would the terrain be like. We can assume, that there is some sand and some boulders, but we cannot tell what would be the bearing capacity of the sand and what would be the size and distribution of the boulders. The largest amount of information on planetary surface composition considers nowdays the Moon and the Mars. From these two the Mars is currently more interesting regarding the missions and landers being planned at the moment.

Having already visited on surface of Mars (with the aid of robotic landers), one can already make some assumptions on size and distribution of the rocks on Mars surface, and one already knows, that sand appears to have a good bearing capacity there. Therefore moving around on Mars surface is merely a question of generating the necessary propulsion force and avoiding to get stuck on any obstacle, that could be a boulder, a sandy dyne, a slope or even a canyon.

In order to avoid obstacles there are basically two options: a) navigate among obstacles and avoid them, and b) build a robust platform that can overcome the obstacles. Obviously the optimal solution uses both approaches; one cannot build such a big robot that would never fall or get stuck in any size of a slope, crack or canyon; as for an example. It is obvious that for a small vehicle a small object can become an obstacle, while a large vehicle usually can overcome larger obstacles. It is also clear, that on a planet surface there usually exist numerically much more small obstacles than large ones. Therefore, navigation needs for a moving robot increase rapidly as robot size decreases, unless robot mobility is increased significantly to overcome the obstacles.



	Maximum	Minimum	Units
Terrain assumptions			
Percentage of rocks with size bigger than 0.5 m in the landing site	1.00		%
Percentage of rock coverage (rocks from 10 to 20 cm high)	20.00		%
Max slope	15.00		deg
Percentage of gaps with depth bigger than 0.25 m and width less than 0.25 m	1.00		%
Max altitude landing site	1.00		Km

Figure 1, Anticipated model of Martian terrain. [RD 2]

This leads us to one possible conclusion (among several possible conclusions): to build a robust and reliable moving robot it must either: a) be small in size and navigate with high performance (like a snake or a mouse etc.), b) be small in size and have exceptional locomotion capability to overcome any obstacles (i.e. climbing, flying, jumping, like a grasshopper) or c) be large enough to overcome most of the expected obstacles (and have some navigation to avoid the larger rocks or cracks) (like an elephant).

Intelligent mechanical models of snakes, mice, cockroaches etc. have already been developed. However, although the corresponding biological creatures living in Martian-like environment in deserts have amazing mobility, so far the robots have not demonstrated such impressive locomotion capability, speed or payload capacity, which would justify their superiority as a surveying rover platform. Either they are too small to carry any payload, or they become far too heavy and clumsy. Never they have been fast. Wheeled vehicles do have capability for fast motion and payload capacity too, but their performance decreases rapidly when terrain becomes soft or uneven.

It is desirable to develop new locomotion methods that would exceed performance of currently familiar systems. In question then become the small vehicles with exceptional locomotion capability, or more large vehicles with novel techniques that would solve problematics with mass and power generation. Biology can offer some references.

3 Background

3.1 Biomimicry

Biomimetics is essentially the practise of taking ideas and concepts from nature and implementing them in a field of technology. Already Leonardo DaVinci studied plants and animals and designed mechanical solutions to provide similar structures and operations. Biomimetic engineering is, like any organism or function that it is imitating, highly multidisciplinary, and includes aspects related to materials, structures, mechanical properties, computing and control, design integration, optimization, functionality and cost effectiveness.

As robotic exploration of the solar system continues, the requirements for autonomy and robustness will increase; the long communication times involved between the Earth and Mars for example mean that the next generation of surface rovers will be required to act autonomously. Abundance, survivability and performance of terrestrial plants and animals demonstrate the potential that biomimetic engineering could provide. The application of biomimetic locomotion to the Martian surface offers the possibility of increased robustness and failure tolerance. [RD 3]

3.2 Ariadna-program

The main objective of Ariadna is to enhance cooperation and facilitate research partnerships with universities and research departments linked to universities. Subjects include theoretical physics, power systems, propulsion, trajectory design and optimisation, informatics and applied mathematics, biomimicry, and other subjects in which both space systems engineering competence and specific theoretical knowledge are required. This study is a response to Call 03/6201 - Biologically inspired solutions for robotic surface mobility. [RD 3]

4 Locomotion in nature

To begin with one should first check, what else has been already invented in nature. The possible advantages of biomimetic locomotion are a robust response to obstacles and rapid movement over complex and unpredictable terrain. The correct mode of locomotion is obviously environment-dependent, and the suitability of proposed techniques must be justified in the context of the environment in which they will operate. From this follows that investigation of the utilization of already-present environmental features to aid the locomotion can reveal interesting solutions: like rolling down the slopes (totally free energy), or flying around carried by the wind (like a dandelion seed). The 'rolling bush' or 'tumbleweed' does the both: rolls around driven by the wind.

Water flow or snow lavine express exceptional traveling capacity: although without any propulsion of their own, they travel driven by the gravity and pass by or over any obstacles placed in the way. Here the traveling object has enough flexibility to naturally go around or over the obstacle. Similar action takes place in car tire: small stones and bumps enter inside the tire, while center of gravity of the tire/car travels straight forward above the 'obstacle'. In a similar manner a large 'almost flat' tire or a flexible ball would overcome any smaller obstacles on Martian surface.

Considering the efficiency and speed of the wheeled vehicles, it seems a bit surprising that nature does not seem to utilize a wheel-design at all, despite of a few curiosities among insects and sea-animals.

Some bacteria boast a marvelous swimming device, the flagellum, which has no counterpart in more complex cells. These bacteria swim by rotating their flagella. So the bacterial flagellum acts as a rotary propellor. The flagellum is a long, hairlike filament embedded in the cell membrane. The flagellin filament is the paddle surface that contacts the the liquid during swimming. At the end of the flagellin filament near the surface of the cell, there is a bulge in the thickness of the flagellum. It is here that the filament attaches to the rotor drive. The motor that rotates the filament-propellor is located at the base of the flagellum, where electron microscopy shows several ring structures occur [RD 30]. Obviously these bacteria do utilize a sort of rotary mechanism, but not as directly as a wheel for locomotion.

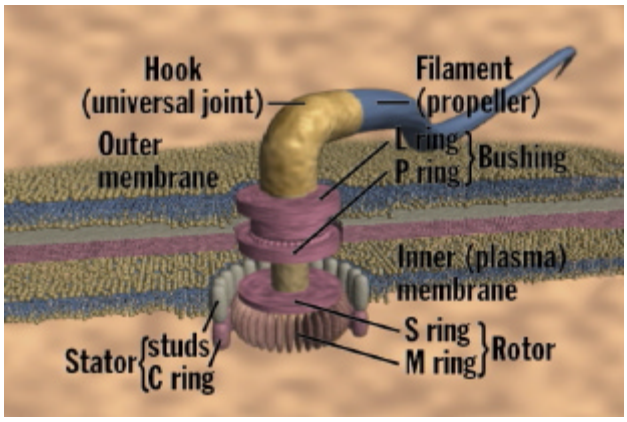


Figure 2, A bacteria utilizing a rotary mechanism. [RD 30]

Several smaller and bigger animals can also adopt a form of a wheel and rotate in a more or less controlled manner. However, even these creatures do not have any wheels, but they roll themselves, as a unity.

Stomatopods are elongated organisms with relatively "stumpy" legs who live mainly in shallow waters. Occasional storm may sometimes drop them right in the middle of a beach, and here the creature's swimmerets and legs are of almost no use whatsoever. Some stomatopods have evolved a rather ingenious solution to the problem. The small stomatopod Nannosquilla decemspinosa lives along the Pacific coast of Panama, and is frequently washed on shore by waves. This mantis shrimp is even more elongated looking than the typical specimens that are sometimes found in live rock, and its legs are completely inadequate when it comes to getting the animal safely back to its ocean burrow. Incredibly, N. decemspinosa moves across the sand by backwards somersaulting, moving as far as 2 meters at a time by rolling 20-40 times, with speeds of around 72 revolutions per minute at 1.5 body lengths per second (3.5 cm/s). Researchers estimate that the stomatopod functions as a true wheel around 40% of the time during this series of rolls, with the remaining 60% being those times when it has to "jumpstart" a roll by using its whole body as a single "leg" to thrust itself upwards and forwards. [RD 31] This little creature shows clearly an active method of locomotion by rolling. The rolling energy seems to be adopted from kinetic energy of body motions.

Figure 3, Image showing movement of N. decemspinosa as it rolls along a beach. [RD 31]

The salamander Hydromantes platycephalus has adopted a novel antipredator mechanism that consists of body and tail coiling and limb tucking followed by passive rolling escape. Although coiling is widespread among salamanders, H. platycephalus performs it in the novel context of the steep slopes of the northern Sierra Nevada of California. This results in the peculiar anti-predator mechanism of rolling escape. [RD 32] Obviously the defense mechanism is active; i.e. the salamander adopts a spherical posture actively, but the following rolling phase is passive; the animal will roll downwards if it happens to be located an a slope steep enough.

Possibly inspired by above mentioned salamanders the Dutch artist Escher imagined and illustrated a 6-legged animal that also had an ability to cover large distances by rolling. The animal would give and maintain speed by pushing forward with its legs. Escher also describes procedures how to enter into rolling mode and two options how to return into walking mode. Entering is a straight-forward curling of animal body. Return to walking mode can happen in two ways; the animal can straighten abruptly which finally sets the animal laying on its back, or the animal can un-curl slowly in a controlled manner starting from the tail and so return to original walking mode. [RD 33] Locomotion is clearly active, and while rolling itself is continuous, the power implementation (by kicking speed from ground) is sequential.

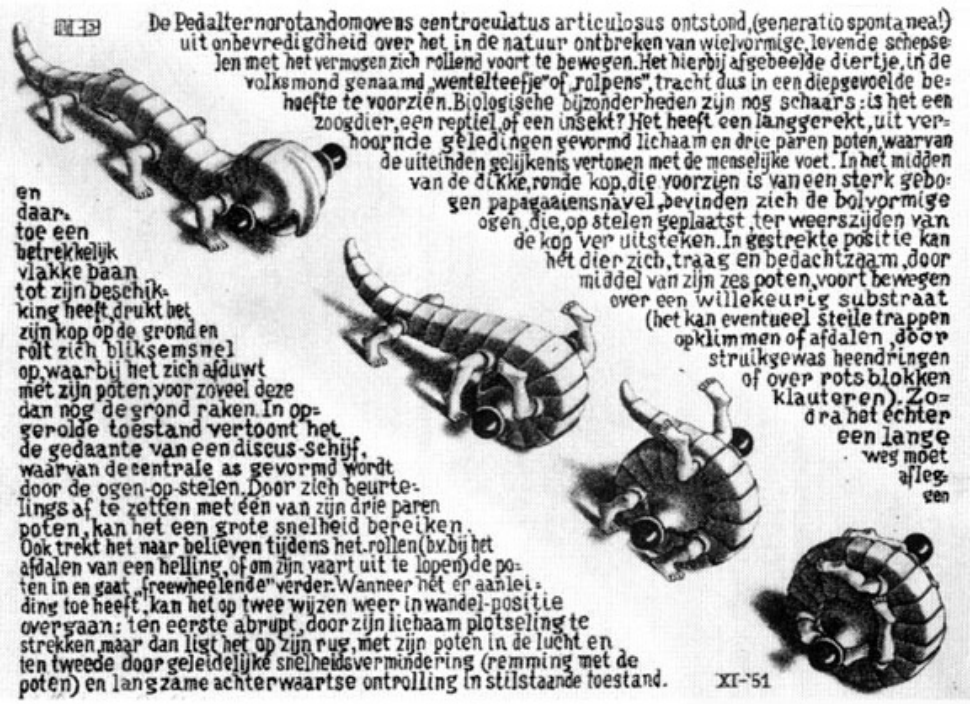


Figure 4, M.C. Escher's Curl-up
©1998 Cordon Art B.V. - Baarn - Holland. [RD 33]

Some existing animals; at least bears, chimpanzees and humans are able to curl-up in a similar way and do somersaults. Human athletes can also cartwheel. Possibly due to our nervous system, vision, and balance, and also due to our physical structure these methods of locomotion can not be utilized as mean for covering long distance, but are only used for fun and to present physical skills. However, these stunts indicate methods to transfer energy to rotational motion. Obviously these stunts use legs and hands to push speed from ground, and rotation is assisted with unbalancing body weight.

Considering the limited existence of a wheel in nature, a conclusion can be made that the nature has not invented it all, and not all man-made inventions are bad. An ultimate solution might well be a hybrid construction of natural and man-made inventions. Or the construction may even rely on solutions that are not based on nature nor technology, but on human imagination. As an example can be mentioned the Work Partner (to be presented later as a reference project) that is a hybrid construction of walking (natural), wheeled (technical) and centaur (imaginative, or even divine creature) features.

4.1 Robustenss

Most of natural creatures have some degree of robustness. Plants seem to present more robustness than animals, possibly due to inability of moving or protecting themselves.

Most of animal organs are doubled, but not all. Animals usually can survive even if one of their four (or even two) legs is accidentally lost, -provided that there are no other symptoms, like septicemia. This also requires that animals are still able to get the food they need. A disabled hunter may be in serious trouble. Insects and millipedes have a good robustness when regarding the legs and locomotion capability. Multiplication of limbs adds robustness for locomotion, which in many cases is the key for survival.

Plants in general have multiple branches, both in the root system and in leafage. Loss of some roots or branches or leaves is not usually dangerous. Even the flowers and reproduction organs are multiplied. Dandelion seeds, like most of the plants, utilize multiplication of the seeds to guarantee spreading of the plant, even in the case when most of the seeds would fall into non-fertile or hostile ground. The Russian thistle –presented below- when already dead and dry can get rid of old roots and be windborne and disperse seeds over new growing places. Reasonable loss of branches during traveling does not affect on its locomotion or reproduction capability.

4.2 Russian Thistle

The Russian thistle looks like the skeleton of a normal shrub. Plants may be as small as a soccer ball or as large as a Volkswagen beetle. Most people, however, would fail to recognize the seedling and juvenile plant's bright green, succulent, grass-like shoots, which are usually red or purple striped. By autumn the plant has reached maximum size,

flowered and begun to dry out. A specialized layer of cells in the stem facilitates the easy break between plant and root, and the plant can be carried away by the wind. As it rolls down a desert road a Russian thistle disperses seeds, which typically number 250,000 per plant. Each seed is a coiled, embryonic plant wrapped in a thin membrane. To survive winter without a warm coat, the plant does not germinate until warm weather arrives. When moisture falls, the plant is ready to uncoil and germinate. All that is required are temperatures between 28 and 110 degrees Fahrenheit. It then quickly sends up two needle-like leaves and begins to shoot skyward. [RD 37]

Tumbleweed," "Russian thistle" caught on a barbed wire fence.

Figure 5, A Tumbleweed [RD 37]

4.3 Dandelion Seeds

A dandelion is really many tiny flowers bunched together. After a dandelion blooms, each of its flowers produces a seed. Each seed is attached to a stem with white fluffy threads. Dandelion seeds are carried away by the wind and travel like tiny parachutes. A strong wind can carry the parachutes miles away from the parent plant.

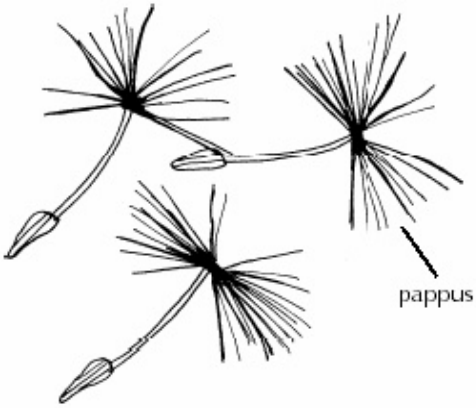


Figure 6, Dandelion seeds

4.4 Maple Seed

Maple seeds come in a variety of shapes, sizes, and colors, but all of them rotate autonomously during falling.

Maple seeds are superb autorotating helicopters. They begin rotating almost from the moment they are released from the tree. Even seeds that are poorly shaped or have badly damaged blades rotate with ease. Autorotation takes place because of the asymmetrical nature of maple seeds. The center of mass of the seed is shifted well to one end while its center of lift is approximately in the middle. The rotation actually inscribes a cone around the axis of fall. The shape of the cone will vary depending upon the aerodynamic qualities of the seed's blade. A blade with minimal lift properties will inscribe a steep-side cone while a blade with strong lift properties will inscribe a very flattened cone. [RD 38]

Some seeds have wings that let them fly on their own. The seeds from maple, elm, and ash trees have curved wings to let them stay in the air longer. Maple seeds twirl and spin around. The wind will pick up the Maple seeds and carry them to suitable land. They will then drop and sprout a new Maple tree. [RD 39]

Figure 7, Maple Seeds.

4.5 Hoppers

Kangaroos, many birds, mice and humans use hopping either occasionally or as the standard mode of locomotion. Hopping involves simultaneous movements by both (hind) limbs simultaneously to effect an intermittent air borne gait that like running relies on the storage of kinetic energy in elastic elements. For small animals aerodynamic drag forces are substantial. Another observation is that jump height is a function of square of initial velocity, therefore jumping muscles that can contract twice as rapidly will result in a jump that is four times as high. For this reason, rapidly contracting muscles are associated with jumping. To obtain maximal initial velocity many small animals use loaded biological springs for jumping rather than a rapidly contracting musculature. In this way,

the velocity can exceed that of even a rapidly contracting muscle, hence height can be optimized. [RD 40]

A flea jumps up to a height of about 0.5 m. It accelerates across a distance of about 2 mm. This leads to an acceleration of 250 g. Since the jumping height of a flea is strongly influenced by air resistance and the acceleration is not uniform, it has, in reality, a greater initial acceleration. There are other animals with an even greater acceleration. A man can only achieve up to 3g with a standing high jump.

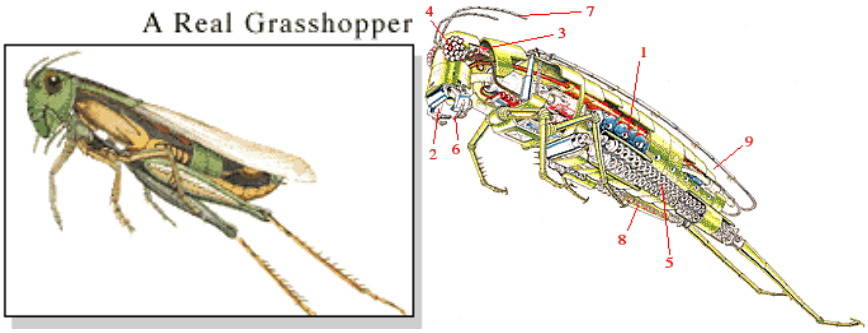


Figure 8, Grasshopper and artistic view of a robotic one. [RD 34]

4.6 Marine animals

Marine animals experience the hydrostatic lift that reduces effective weight of their body. Thus their limbs often are wery thin and long; seemingly quite weak compared to the size of the body. Byouancy allows long, low-mass and low-power locomotion structures that provide effective means of locomotion under the sea. Consider such examples as crabs or octopus.

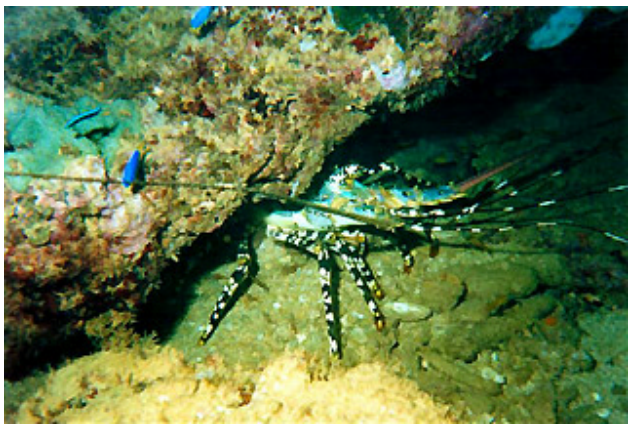


Figure 9. A lobster experiences nearly zero-weight on the bottom of the sea.

5 Locomotion on Mars and other planets

5.1 Objective

Purpose of a mobile robot on (or even below or above) planet surface is to enlarge the area to be investigated, and to concentrate investigations on subjects with most scientific interest. To fulfill this objective the robot can carry out necessary investigations while it is moving around, or it can transfer the instruments to the places of interest –or soil/rock samples back to the lander for more accurate investigations.

Area covered by the robot depends on its speed and available traveling time, as well as on possible tether and communication methods that bind it on the lander. The traveling time may be limited by power sources and mechanical durability. Locomotion speed depends on rover cross-country capabilities, power, navigation and autonomy.

The strongest limitations for mobility are the available power and challenges caused by the terrain, which deserve close investigation when developing new efficient locomotion methods. If challenges caused by complex geography can be reduced (i.e. cross-country capability can be increased), needed locomotion power can be expected to be reduced and locomotion speed increased.

5.2 History

A quick glimpse on past planetary rovers and vehicles reveals majority of wheeled vehicles, while also a couple of novel designs has been presented.

5.2.1 Phobos hopper

For the Venusian moon Phobos hopping was found to be a suitable way of mobility because of its low gravity (1/500 of that of Earth). The Russian PROP-F hopper was designed to travel on Phobos' surface. This robot was mounted on the Phobos 2 spacecraft. Contact to the spacecraft was lost in 1989 before deployment of the hopper [RD 5] Hopping mechanism relies on release of spring stored energy, and the 'aerials' that are used to re-position the hopper after landing in correct position. The spring could be re-loaded with the aid of an electric motor.

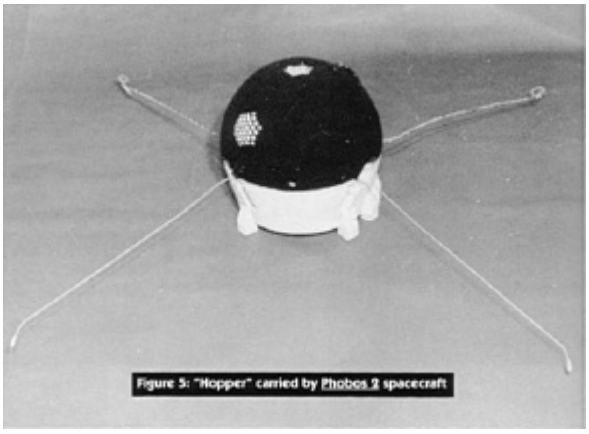


Figure 5: "Hopper" carried by Phobos 2 spacecraft

5.2.2 Soviet Mars-rovers

In 1971 the Soviet Mars 2 and 3 missions carried two small robotic rovers onto Mars. Another mission crashed onto Mars, while contact to the other was lost before deployment of the rover. The rovers were connected to the lander with a 15-m long tether. Mobility was provided by two skis that were used to walk along the surface. Between the steps the rover would lay down on its belly. Opposite direction of ski-motion would make the rover to turn. With an external mechanical sensor the rover would detect any obstacles and the would autonomously back-off a few steps and then change direction before continuing it's travel. [RD 5]

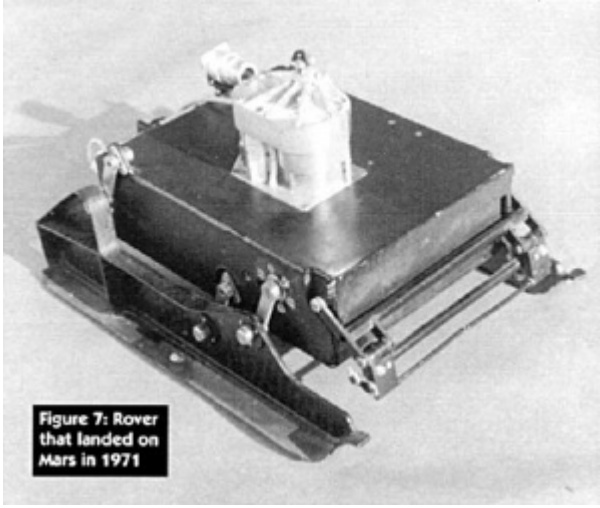


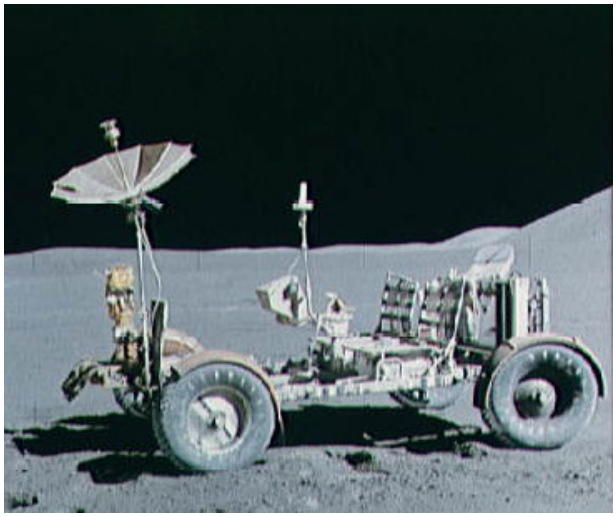
Figure 7: Rover that landed on Mars in 1971

5.2.3 Lunokhod

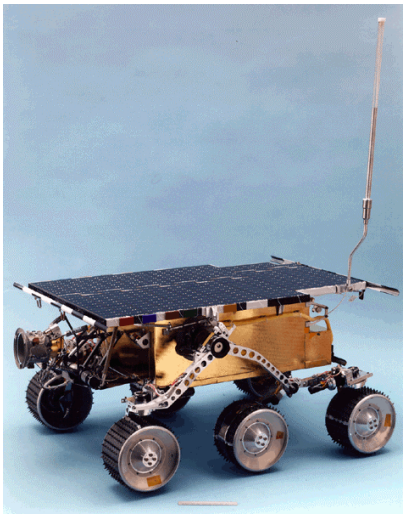
The Soviet Lunokhod-vehicles explored the surface of the Moon. The Lunokhod's mass was 750 kilograms, and its speed was 0.8 to 2 kilometers per hour. The robot was tele-operated from Earth. The Lunokhod carried an airtight compartment with a temperature-control system, an isotope heat source, a radio and television transmitter, a command receiver, a power plant, a remote control, a small-frame television, panoramic tele-photometers and scientific instruments. [RD 5]

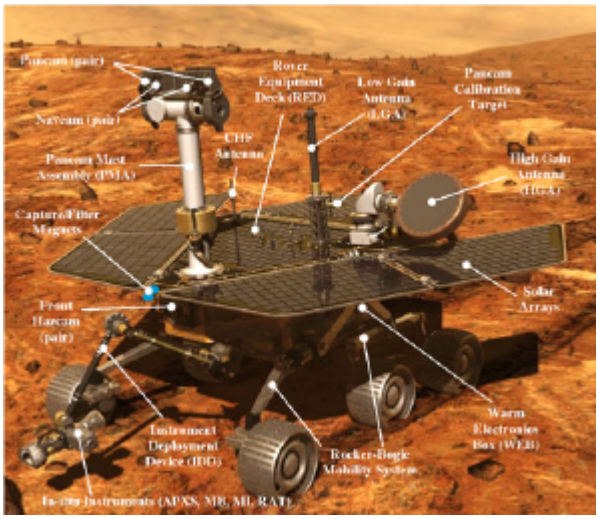
5.2.4 Apollo Moon vehicle

The Lunar Roving Vehicle (LRV) was an electric vehicle designed to operate in the low-gravity vacuum of the Moon. Three LRVs were driven on the Moon. In practice the LRV was an electric car used by the astronauts. The LRV had a mass of 210 kg and was designed to hold a payload of an additional 490 kg on the lunar surface. The frame was 3.1 meters long with a wheelbase of 2.3 meters. Two 36-volt silver-zinc potassium hydroxide non-rechargeable batteries provided power with a capacity of 121 amp hr. [RD 6]



5.2.5 Sojourner, Opportunity, Spirit





The NASA rovers ‘Sojourner’, ‘Opportunity’ and ‘Spirit’ present the latest roving technology on surface of Mars. The Sojourner being of a smaller size (11 kg) and the two other of a larger scale (185 kg) present all a similar basic structure with a rocker-bogie type chassis equipped with 6 wheels. The Sojourner could travel 40 cm/min while the bigger ones have a speed of 3 m/min. (Images [RD 7], [RD 8].)

5.2.6 Pluto

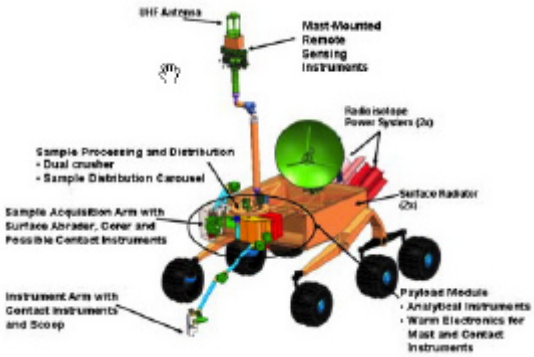
Pluto (planetary under surface tool) as the mole is called, has the ability to crawl across the surface at the rate of 1cm every 5 seconds. Pluto’s locomotion is based on internal hammering mechanism and shocks, like in terrestrial penetrometers. Pluto can collect samples in a cavity in the tip, which opens when the mole reaches a sampling location. The mole could crawl up to three metres away from the lander, including the burrowing phase; it is recovered by rewinding the cable with a winch. The device has a total weight of 950g and power consumption only a couple of watts. [RD 9]

5.3 Future

Plans for coming planetary vehicles seem to rely largely on wheeled rovers. However, also a large magnitude of research is being carried out to develop alternative solutions. Main drivers for the new innovations are in general smaller mass, smaller power, longer life time, increased area coverage and higher robustness.

5.3.1 Mars Science Laboratory

Mars Science Laboratory would be a rover similar to previous ones, but significantly larger. A long duration rover equipped to perform many scientific studies of Mars is planned for a late 2009 launch. The mission is planned to last at least one Martian year (687 days). The rover would be four- to five-times larger than the current Mars rovers, i.e. it would have a size of a mini-van. [RD 10]



5.3.2 Marsokhod

Marsokhod is a Russian 6-wheeled rover with articulated body. It possesses remarkable locomotion capability and multiple locomotion techniques. Marsokhod has been studied widely in Europe, USA and Asia for future Mars and Moon missions. (Image [RD 5])

5.3.3 JPL Tumbleweed

The Tumbleweed robot developed at NASA JPL has been demonstrated and tested successfully in small 1.5 m diameter scale on deserts and Antarctica. The Tumbleweed rover derives its name from the dead sagebrush balls that blow across the deserts of the American southwest. Likewise, the rover's only means of locomotion is the ambient wind. A 6-meter diameter Tumbleweed is envisaged for deployment on the surface of Mars. Such a ball could potentially serve as its own descent and landing system, replacing parachutes and airbags. While its mobility is dependant on the wind, the Tumbleweed rover will have some ability to control its speed by regulating its level of internal pressure. The Martian Tumbleweed would be comprised of a 20 kg ball and a 20 kg payload suspended from the center. Traveling at speeds up to 10 m/s in the 20 m/s wind of a typical Martian afternoon, the ball is expected to climb 20° slopes with ease. [RD 11]

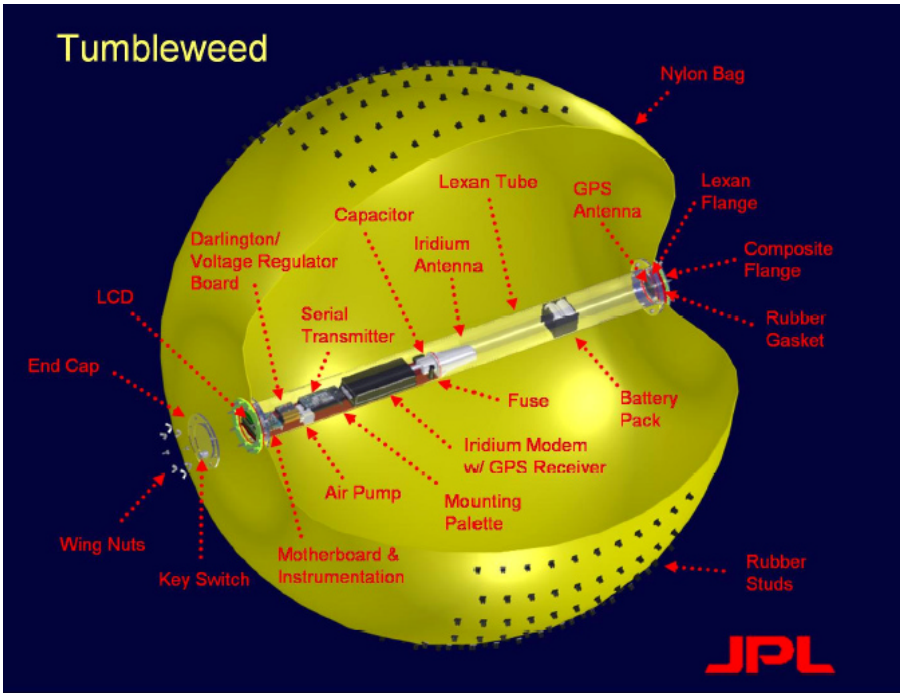


Figure 10, The Tumbleweed developed in JPL. [RD 11]

5.3.4 Balloons

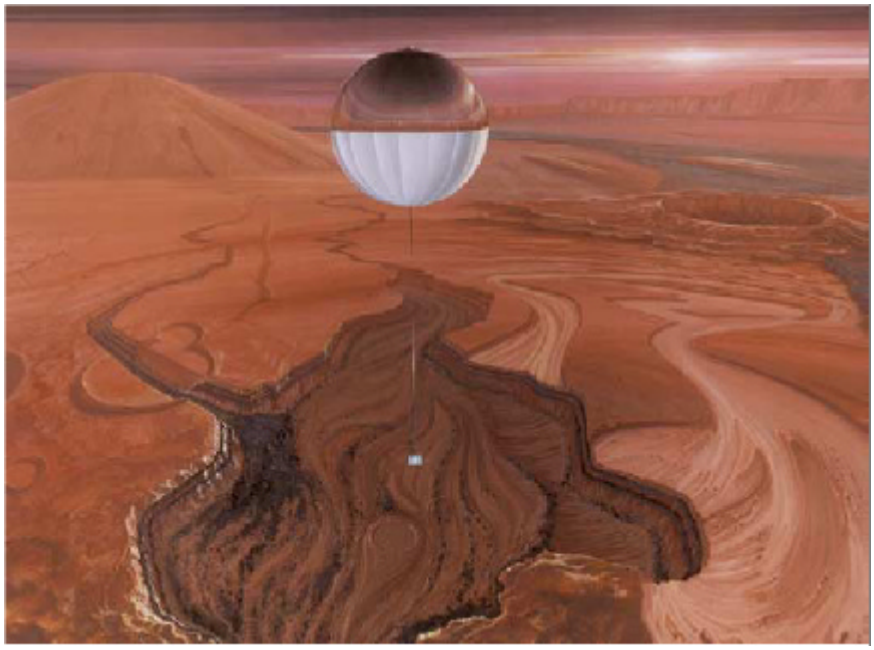


Figure 11, A balloon over Martian surface. [RD 12]

Balloons could fly much closer to the surface of Mars than orbiters, and much further and faster than rovers on Mars surface. Balloons have been flying for decades in Earth's stratosphere, which has an atmosphere as thin as that on the surface of Mars. Conventional stratospheric balloons have lifetimes limited to a few days because of the daily heating and cooling of the balloon.

Another type of a balloon, namely a solar Montgolfiere balloon, does not have to be inflated with a light gas such as helium. Instead, the balloon would fill up with Martian air. The balloon would then be heated by the sun, which provides buoyancy. The balloon remains buoyant until the sun goes down. During the night the ball would descent onto Mars surface, but upon heating of the daylight, the balloon would rise into air again. [RD 12]

5.3.5 Flyers

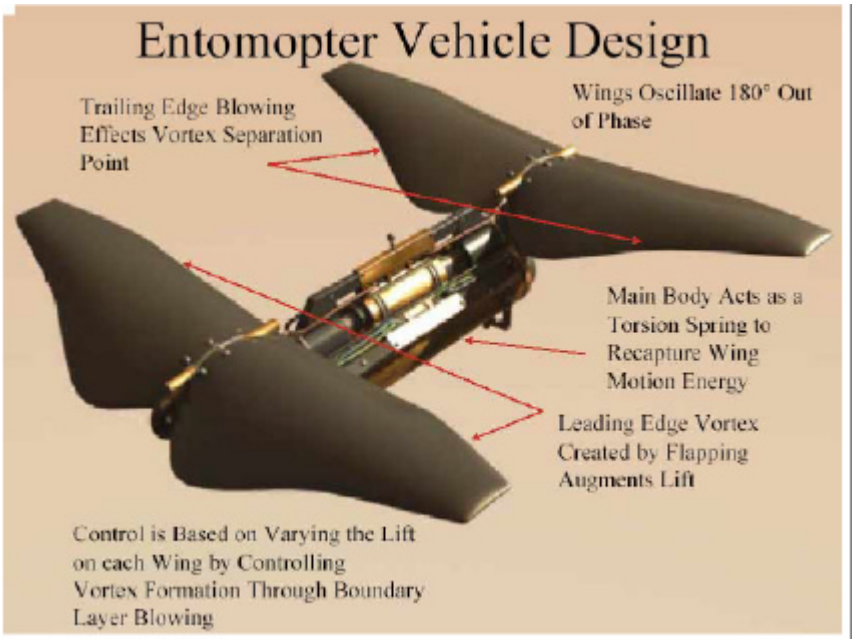


Figure 12, A novel entomopter vehicle for Mars exploration. [RD 12]

Currently is being developed a robotic airplane that could navigate on its own without human pilots. Due to thin Martian atmosphere taking off from the ground would require very big wings or a very high take-off -speed. Alternatively the plane could be dropped off from the lander during descent into Martian atmosphere. Although this flight would be quite short (less than an hour), and shorter than a balloon flight, an airplane would be more controllable and it could be directed to closely approach areas of scientific interest. [RD 12]

5.3.6 Swarms

A large number of micro-instruments are planned to be released into Venusian atmosphere by a carrier vehicle. The interest lays in acquiring reference in-situ data for atmospheric pressure, temperature, light-intensity, humidity and chemical atmospheric composition. A number of microprobes would be carried in the balloon gondola, such as maple seeds in a pod. This microprobes should target a size of 10 cm^3 at a mass of preferably less then 0.1 kg. This swarm of probes will plunge through the dense Venusian atmosphere, transmitting acquired data back to the balloon. [RD 13]

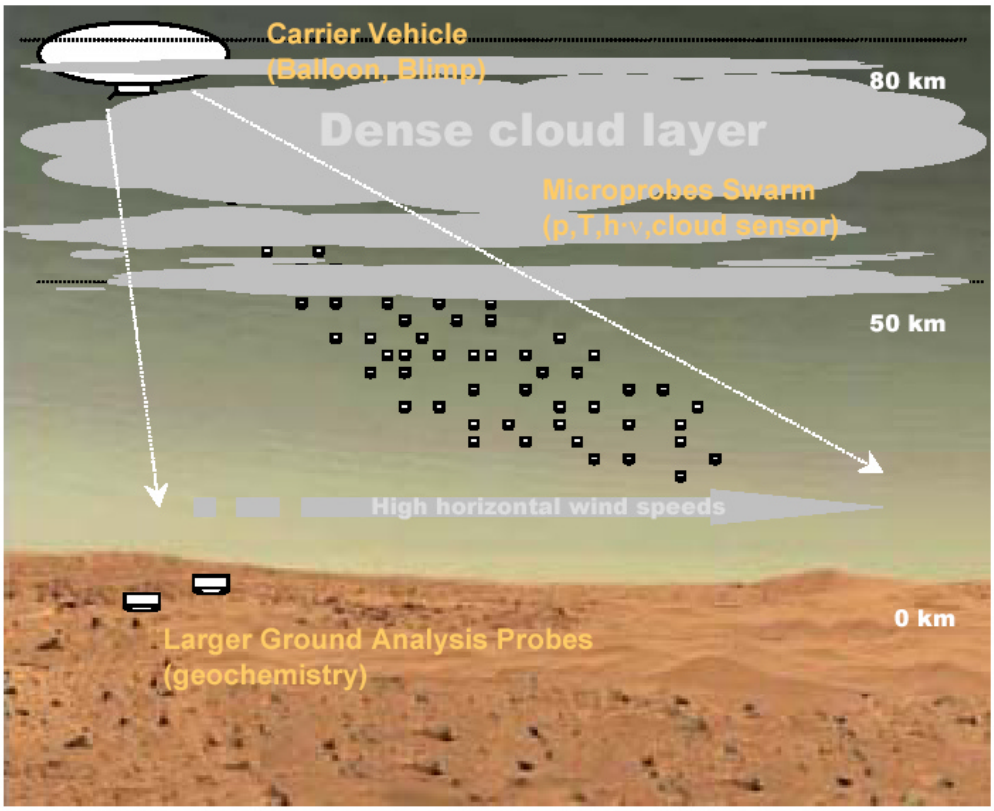


Figure 13, A microprobe swarm exploring a planetary atmosphere. [RD 13]

The advantage of swarms is that several atmospheric descend probes, on diverse locations in the atmosphere, will enable a good scientific output and provide a large amount of in-situ data. Swarms can be deployed in different locations on the planet, by different carrier vehicles (e.g. a balloon floating high in the planetary atmospheres, a blimp, a glider). State of the art MEMS and IC related technologies could be used to develop a miniature microprobe. In order to control the atmospheric descent, a passive stabilisation system such as, auto-rotation in maple seeds, may be implemented. A fast descend induced rotation can be used to generate the necessary electric energy for powering the probe.

Localization, tracking and communication functions can be passed to the carrier. Localisation and tracking of free-moving microprobes in a large volume is a problem yet to be solved.

Two localisation approaches exist:
- Microprobe based: the microprobe is equipped with localisation means (e.g. integrating gyros, altimeter) which allow the probe to know its position

- Carrier based: the carrier derives the position of the probes (e.g. scanning and ranging mechanism) [RD 13]

6 Locomotion studied at HUT

6.1 Rollo

Figure 14, Mobile Ball-Shaped Robot

The ball robot is a mobile robot based on a ball structure. The robot has two degrees of freedom which it can use for selecting the rolling direction and then for rolling back- and forward. Mobility is based on internal off-balance, i.e. the mass inside the robot ball is moved away from the center which makes the ball to rotate. The robot is easily made liquid and gas proof, it recovers easily from collisions, the cover can be made mechanically durable and the robot cannot turn over or fall down. All the robot systems are fully constrained inside the ball cover.

The robot is designed to act as a small platform to carry sensing devices or actuators in an environment where stability of the platform is critical, like in surveying unstructured hostile industrial environment or exploring other planets, or simply being a part of a human place, like office or home, which has not been designed for mobile machines. Dynamical properties, motion control and mechanics have been studied with the prototype robots and simulator. The spherical construction offers extraordinary motion properties in cases where turning over or falling down are risks for the robot to continue its motion. Also it has full capability to recover from collisions with obstacles or another robots traveling in the environment. Prior to current design two earlier versions for the robot IDU (Inside Drive Unit), both shown in the picture below, were built. The first version (on the right) was quickly replaced with the second version on the left. The

second generation had two completely de-coupled freedoms which made it easy to control and drive. However, requirements set for the spherical shell were most stringent and the cover was difficult and expensive to manufacture. The current third generation allows a transparent and inexpensive cover.

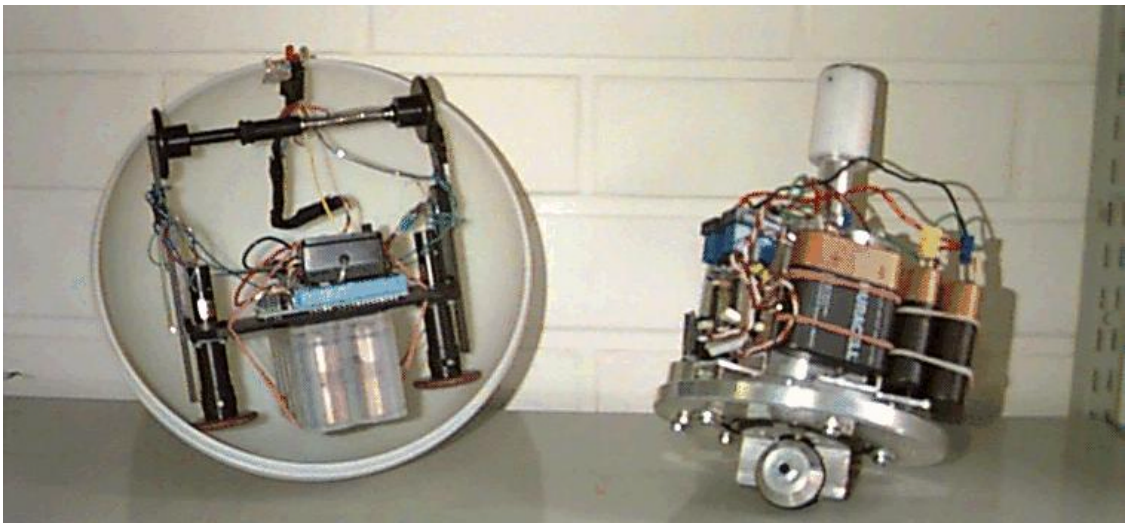


Figure 15, Earlier prototypes of the ball robot.

6.2 "Squiggleball"

"Squiggleball" is a small toy that, driven by an AA-battery, wanderers around floor and with an amazing capability gets around almost any obstacle. Squiggleballs were studied when developing the Rollo-robots. The Squiggleball motion is based on ballast drive, see images below.

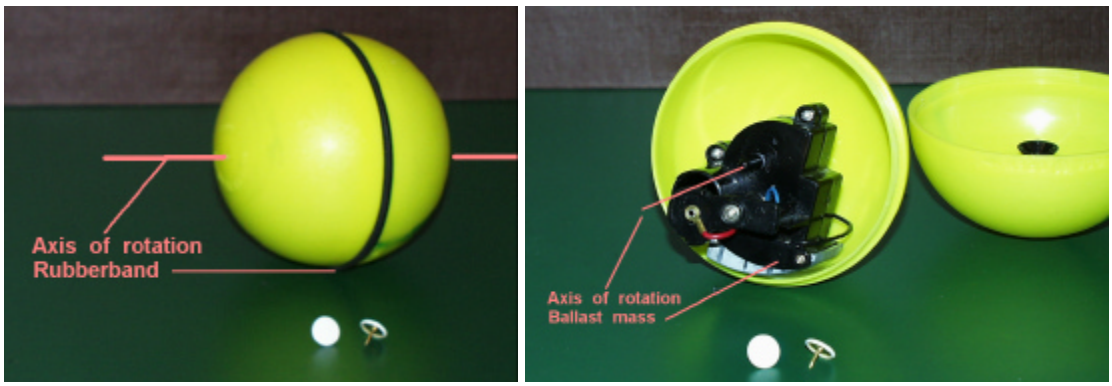


Figure 16, A ballast driven "Squiggleball".

One important feature of the ball is the rubber band running around the ball and sharing the axis of rotation. First of all the rubber band gives friction so that upon contact on an obstacle the ball does not start slipping, but the ballast mass starts to rise around the axis of rotation. As the ballast reaches the top dead center the ball suddenly rotates ½ revolutions backwards. The rubber band also extends a bit outside the sphere surface. This causes the axis of rotation to be slightly tilted from horizontal plane. Because of this, as the ballast mass elevates above the axis, it also generates a torque on sideways. So, as the ball autonomously reverses its rotation for ½ rotations, it at the same time tends to fall aside and in this way automatically changes its direction of motion. Acting in this manner with very simple mechanical solutions this small ball can get around almost any obstacle and it exits also dead-ends of a labyrinth. The tilted axis of rotation makes the ball to arc instead of running straight forward. This way the ball follows any walls in vicinity and finds slots or doors without any intelligence or guidance.

6.3 Mecant

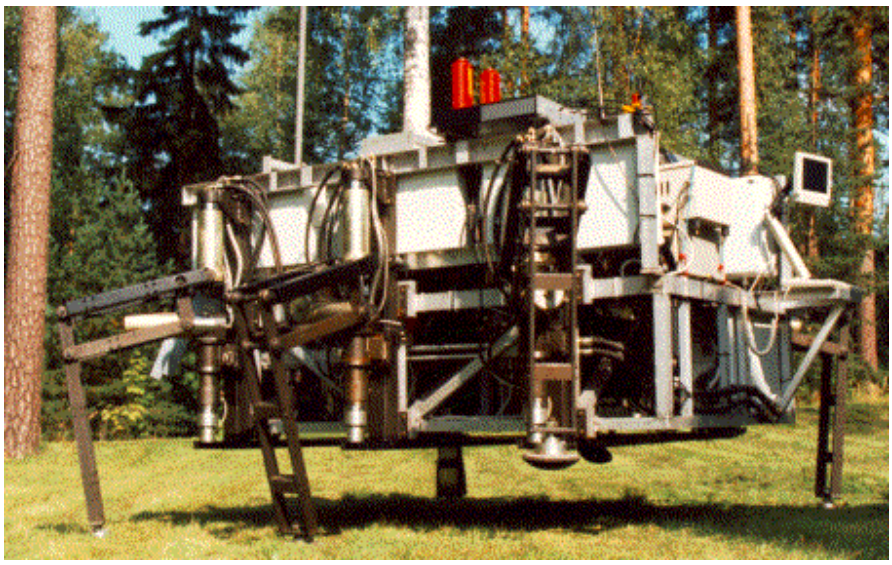


Figure 17, MECANT, the Walking Machine

MECANT is a fully independent hydraulic six-legged walking machine. The machine weighs about 1100 kg and is driven by a 38 kW 2-cylinder ultra-light aeroplane engine with air-cooling. The leg mechanism is a 2-dimensional pantograph with vertical rotation axis thus having 3 d.o.fs and they are driven by hydraulic system. The operator controls the vehicle remotely by the joysticks via the radio link

6.4 WoPa

Figure 18, Work Partner serving robot

WorkPartner's platform called HYBTOR uses a hybrid locomotion system, which combines both wheels and legs to produce active propulsion. Because of its four wheeled legs and articulated body it has very flexible and wide range of mobility. HYBTOR-platform has four 3-DOF legs, a controllable body joint and a wheel in each leg, which makes it capable of moving flexibly on almost all type of terrain. The power system uses batteries and a small 4 kw engine. The overall weight with the manipulator is about 230 kg.

6.5 Swarm-Submar

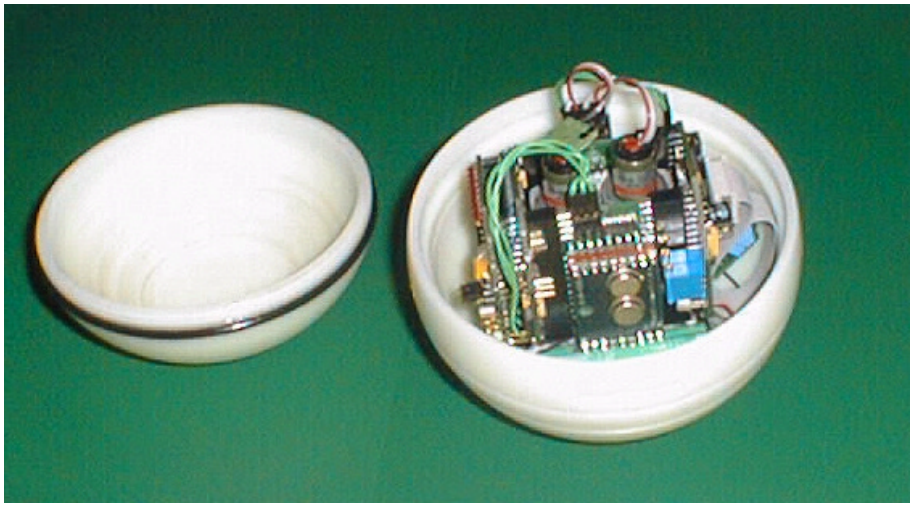


Figure 19, SUBMAR intelligent autonomous miniature robot

SUBMAR is an intelligent, autonomous miniature robot for monitoring of liquid processes. SUBMAR robots measure internal state of the process and can perform small tasks, e.g. injecting reagent and taking samples. Benefits of this robot society concept are fault tolerance, flexibility and simplicity. The robots move semi-actively along the process flow changing their vertical position using diving tanks. SUBMARs have the ability to communicate with other similar robots and with the process operator.

6.6 Rosa-2

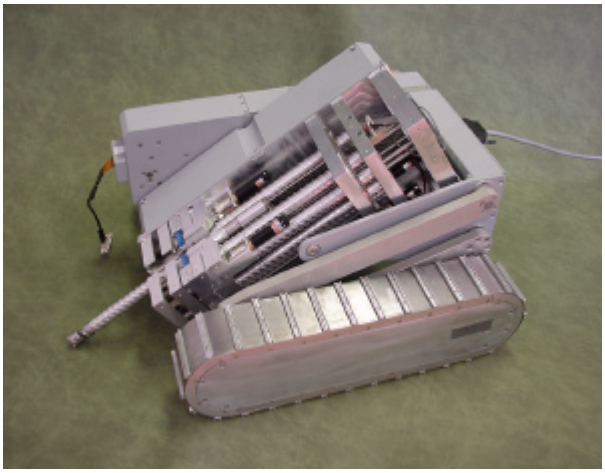


Figure 20, ROSA-2 roving vehicle

The ROSA-2 roving vehicle is a tracked tethered vehicle, serving as a platform for the drilling subsystem. The rover is commanded and supplied with power from the lander via a tether. A lifting bridge allows adjustment of the rover's ground clearance. This feature significantly improves the rover cross-country ability.

7 Mars environment

7.1 Gravity

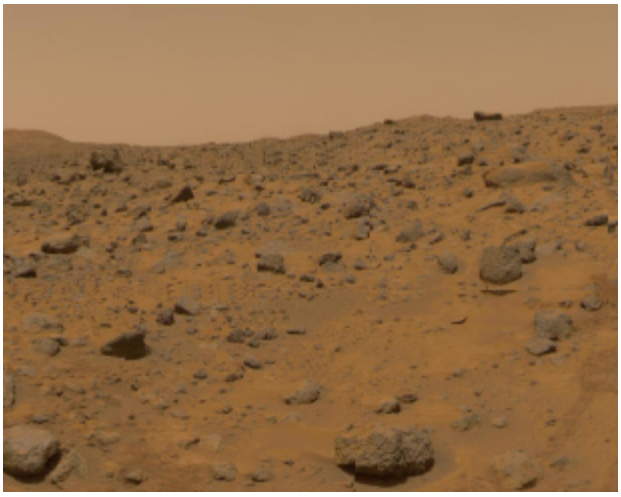
Gravitational acceleration on Mars surface is 0.38 times of that of Earth. According to NASA National Space Science Data Center (NSSDC) Mars Fact Sheet [RD 16] Gravitational acceleration on Mars surface is 3.727 m/sec2.

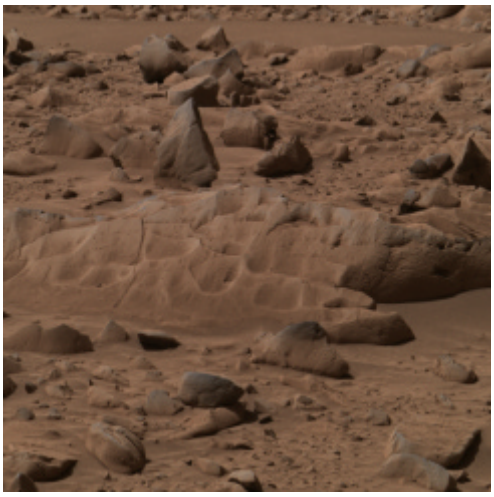
7.2 Terrain and rock distribution

Discussion here on the Martian terrain is limited to aspects concerning mainly surface mobility. Important factors then are slope angles and size and distribution of rocks.

On basis of existing experience load carrying capacity of Martian sand can be expected to be sufficient. Rolling resistance and slippage on loose sand may become a challenge on areas with smaller number of rocks and on sandy dynes.

The table below presents terrain assumptions assumed for an European Mars rover and the following picture illustrates analytical results on the size and distribution of rocks over several Martian landing sites.





	Maximum	Minimum	Units
Terrain assumptions			
Percentage of rocks with size bigger than 0.5 m in the landing site	1.00		%
Percentage of rock coverage (rocks from 10 to 20 cm high)	20.00		%
Max slope	15.00		deg
Percentage of gaps with depth bigger than 0.25 m and width less than 0.25 m	1.00		%
Max altitude landing site	1.00		Km

Figure 21, Images (Courtesy NASA/JPL-Caltech) and anticipated model of Martian terrain. [RD 2, RD 8]

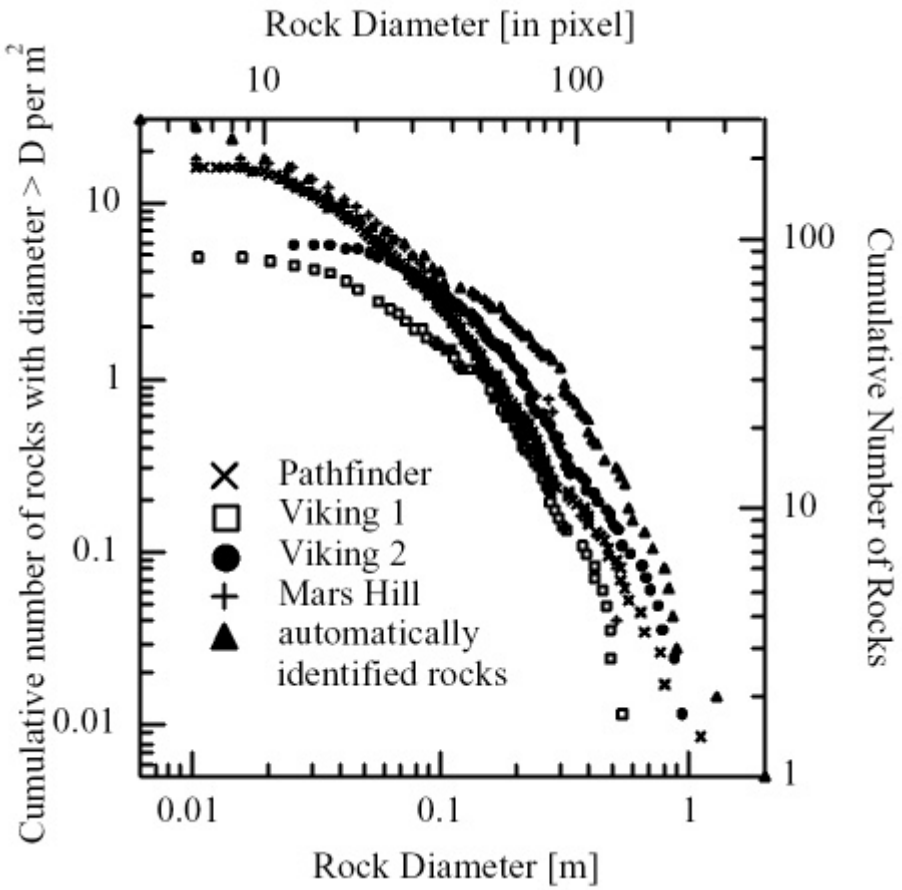


Figure 22, Rock Diameter vs. Cumulative Number of Rocks [RD 19]

Quick study of the illustration above reveals that abundance of rocks 1 m in diameter or larger is roughly 2 per 100 m2, number of rocks 0.5 m or bigger would be 3-30 per 100 m2. Number of rocks 10 cm or bigger would be 1-8 per m2, (or 100-800 per 100 m2). Rocks smaller than 10 cm are not considered since the project expects to develop a system that would overcome those rocks regardless of their abundance.

The rock distribution is mostly fully randomized, i.e. the rocks do not lie within constant distance from each other. Therefore it is practically impossible to calculate any real mean distance between the rocks. In some locations they may be visible and close to each other in high numbers, while only a short distance away may reveal a smooth and rock-free terrain. Variation in rock distribution is large between different landing locations. In the following discussion we consider the worst-case scenario and assume even distribution of rocks.

If we assume that 1 m rock height is the limit for the rover climbing capability, we attempt to calculate mean distance of travel after which the rover probably needs to carry

out an obstacle avoidance procedure (go around or jump over). If we assume that we have 2 large rocks per 100 m2, and we have a 50 m2 circle around each, radius of circle would be ~ 4 m, and distance between the rocks would be ~8 m.

In a similar manner we can calculate the mean distance between rocks of any particular size. The results have been collected into a table below.

The table shows that in the worst case during a 100 meter journey we have to go around 22 rocks bigger than 90 cm, or overcome total of 87 stones bigger than 50 cm but smaller than 90 cm. Every 80 cm travel we have to overcome a stone that is larger than 10 cm but smaller than 20 cm.

The calculation assumes, that the robot would accidentally travel straight from stone to stone, but in reality distance between 90 cm stones would be 11 meters, so even a probabilistic chance would be high to pass by the stones already by coincidence, not to mention possible use of camera and navigation system. Perhaps only one rock out of three happens to lie on the robot's path of travel. Between rocks smaller than 90 cm the mean distance starts to approach dimensions of the robot and probability to meet the stone increases.

It should be noted that this is a worst-case approximation. Variation of rock-distribution may reveal a 10 times smaller number of rocks and more than three times (square root of 10) longer mean distance between.

Rock size	Abundance	Limited size envelope	Abundance	Mean distance between	Number per 100 m travel
cm	per 100 m2	cm	per 100 m2	m	
>100	2	>100	2	8.0	13
>90	3	90-100	1	11.3	9
>80	6	80-90	3	6.5	15
>70	10	70-80	4	5.6	18
>60	15	60-70	5	5.0	20
>50	30	50-60	15	2.9	34
>40	60	40-50	30	2.1	49
>30	100	30-40	40	1.8	56
>20	200	20-30	100	1.1	89
>10	400	10-20	200	0.8	125

Table 1, Calculated mean distance between rocks on Mars surface.

7.3 Atmosphere and winds

Discussion handles atmospheric properties that can be of importance for surface mobility and power generation. Such properties are air pressure, air density, wind speed, and air temperature.

NASA National Space Science Data Center (NSSDC) Mars Fact Sheet [RD 16], The DLR HRSC-Experiment web page [RD 14] and [RD 15] present the following data on Martian atmosphere:

Atmospheric pressure is 7 mbar with quite high variation (25-30%). (Atmospheric pressure on Earth sea-level is 1013 mbar.) Atmospheric density on Martian surface is ~0.020 kg/m3, while on Earth at sea-level it is for standard temperature of 15°C 1.225 kg/m3.

Mean molecular weight of Martian air is 43.34 g/mole. The Mars atmosphere constitutes of the following gases: CO2 (95.32%), N2 (2.7%), 40Ar (1.6%), O2 (0.13%), CO (0.07%), H2O (0.03%). [RD 14]

NSSDC Mars Fact Sheet [RD 16] reports Martian wind speeds 2-7 m/sec (N summer), 5-10 m/sec (N fall), and 17-30 m/sec (dust storm).

Nasa QUEST discussion [RD 20] on the Pathfinder wind measurements indicates that the wind direction rotated throughout the day: from the south at night, westerly in the

mornings, northerly in late afternoon, and from the east in the evening. Naturally fluctuation of wind direction would have an effect on any mobile device driven by the wind. In general, winds were strongest in the early morning hours and were relatively strong around noon. The lightest winds were seen in late afternoon and early evening.

Mars Pathfinder Historical Weather Data [RD 21] reports measurements performed by the Pathfinder over more than 30 sols starting July 4 1997. The landing site in the Ares Vallis region is at 19.33 N, 33.55 W. The prevailing winds were light (less than 10 meters per second, or 36 kilometers per hour) and variable. The illustration below shows how the wind direction and speed changes during one sol and repeats sol after sol. (The wind-speed chart lacks quantitative information on real wind velocity.)

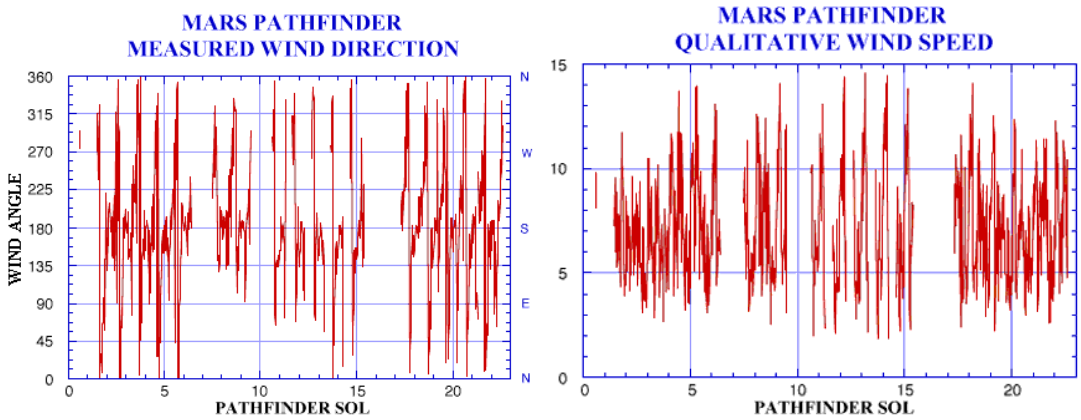


Figure 23, Wind measurements made by the Pathfinder. [RD 21]

7.4 Solar flux

Solar flux is of interest for the project in terms of energy production by direct conversion to electricity with solar cells or by utilization of collected thermal energy with novel techniques.

Length of a Martian day is 24h and 39.6 min, and a Martian year lasts 669.60 Martian days (roughly 1.88 Earth years). Solar irradiance at the Martian distance from Sun is 595 W/m2. [RD 14]

However, because of the harsh atmospheric conditions on Mars, the solar irradiance may be significantly decreased at the surface. [RD 22]

7.5 Temperature

As well as solar flux also temperature is of interest in terms of energy production. However, heat as itself is usually difficult to use as an energy source. In general a temperature difference is needed to produce any activity. This thermal gradient may realize in terms of geometry (cold and hot parts of the system) or in time (repeated heating and cooling).

On Mars surface average temperature is ~210 K-220 K, while Viking Lander-1 measured diurnal temperature range 184 K-242 K [RD 16].

The illustration below shows air temperatures measured by the Pathfinder at Ares Vallis region (19.5 deg N, 32.8 deg W) [RD 21]. In July, 1997, the sun was directly over the 15 degrees north latitude region of the planet. The temperature reached its maximum of 263 kelvins (–10 degrees Celsius) every day at 2 p.m. local solar time, and its minimum of 197 Kelvins (–76 degrees Celsius) just before sunrise.

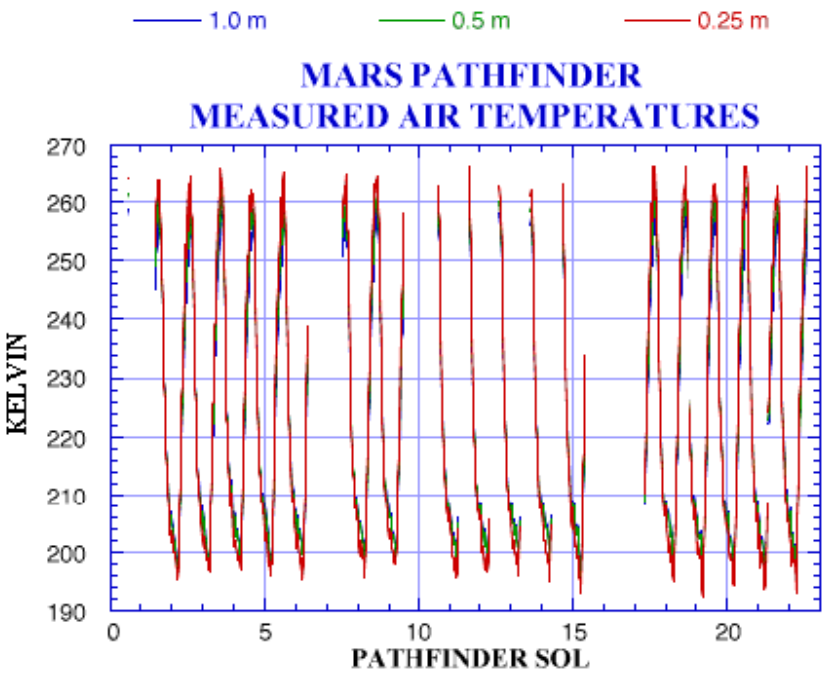


Figure 24, Measured Mars air temperature. [RD 21]

[RD 2] Illustrates calculations of temperatures for sky, air and ground for two cases that are hot and cold (depending on day of the year and location on Mars surface). For the hot case Ls = 180° and latitude = 45°, for the cold case Ls = 270° and latitude = 45°.

The graphs indicate that significant diurnal fluctuation of temperature could be utilized to generate energy on a daily cycle. Also temperature difference between air and ground could be utilized for energy production.

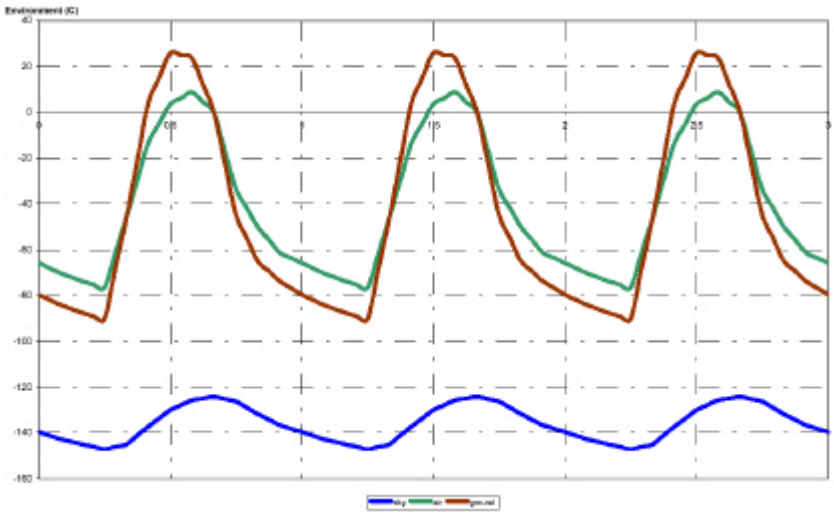


Figure 25, Temperature of Martian Hot Case over 3 Days; sky (blue), air (green), and ground (red). [RD 2]

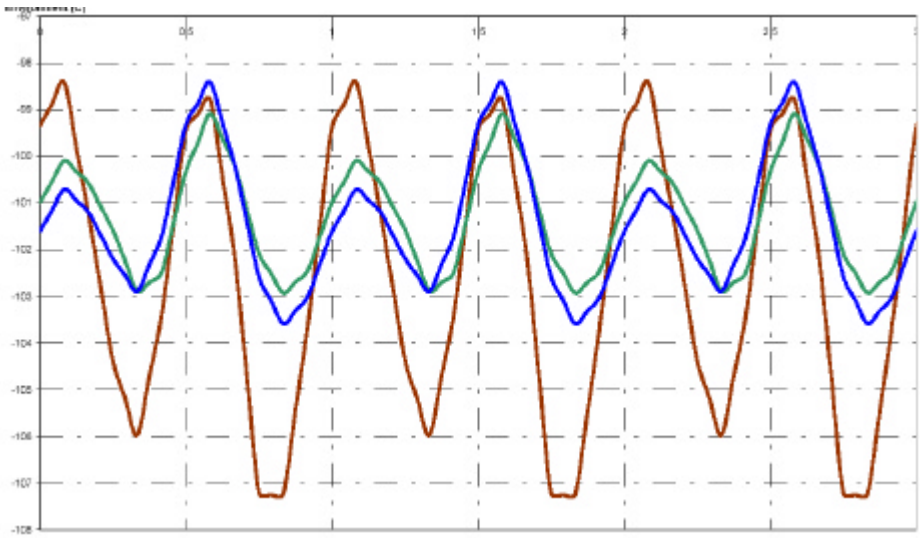


Figure 26, Temperature of Martian Cold Case; sky (blue), air (green), and ground (red) [RD 2]

8 Mission requirements

8.1 Mission description

When landed the mission would start by deployment of the Mars rover from the lander or from the landing configuration and preparation for operation. After deployment the rover can immediately start the first science cycle making the desired measurement and/or sampling procedures and transmitting the data. After the science phase the rover can enter to locomotion phase that lasts until the next science phase. The locomotion and science phases would be repeated until the end of mission.

Length of locomotion and science phases depends on area to be explored, number of measurements to be performed and time needed for analysis and communication. Also some time for household keeping and possibly for battery re-charging may be required.

Survival in harsh Martian environment may become a challenge. Viking Lander 1, landed on July 20, 1976, ceased operation after 2,245 sols (2,306 days) on Mars. The Viking landers were powered by radioisotope thermal generators (RTG). Pathfinder lander was operational for 90 days, and the Sojourner rover lived 84 days. Limited –but still much longer than designed- life time of Pathfinder mission is related to depletion of the spacecraft's battery and a drop in the spacecraft's operating temperatures due to the loss of the battery. For a new long-term exploring mission a few terrestrial-months could be expected, six months would be a significant extension, while terrestrial 1-2 years for a mobile robot would be desirable.

So far the distance that have been explored on surface of Mars has been tens or a few hundred meters. Scientific interest would extend the distance to be traveled to several kilometers, if not tens or hundreds of kilometers. However, in this case a question rises if the roving system needs to communicate directly to an orbiter traveling around Mars, or directly to Earth since connection to the lander may be lost due to long distance.

The table below from ExoMars09 CDF Study Report [RD 2] presents an anticipated scenario for an European drilling mission. Length of locomotion, sampling and communication cycle is 6 days. In this scenario 2 days is reserved for traveling 20 km, one day for drilling and one day for sample analysis. Additional 2 days are needed to transmit all the collected data (680-690 Mbits).

A new long-range Mars rover probably will not carry a drill, but will aim to long-distance traveling with low-mass instrumentation. Thus the drilling phase may be replaced with another analysis-phase, or sampling and data-collection may even be performed during rover locomotion. However, amount of accumulated data with respect to data-transfer capabilities must be considered carefully. Even though the rover transmits data in every possible occasion (twice a day), it takes total of 6 days to transmit expected 680 Mbits of data. Further, the rover must stop all the other actions for the period of transmittal, for

energy reasons and for data-link quality reasons. Thus it is worth considering carefully which kind of measurements shall be performed and resulting effect on cycle length.

#	Phase	Description	Subsystems on	Subsystems off	duration	time counter (days)	note
1	Rover overall initialisation	After landing, all equipments are checked, payload and navigation is initialised, "Alright" signals are sent to Earth	Power, DHS, payload (except drill), payload electronic, camera (only during windows), navigation, Locomotion unit (only partially)		10 hours. (assumption the useful illumination time in one day is 10	0.50	1 day is needed in order to catch the comms window. This phase is not dimensioning
2	Night	The rover goes in sleeping mode	RHUs, power, DHS (only wake-up unit), comms during the visibility windows (0.8 h)	Payload, locomotion unit, navigation	14 hours	1.00	
A first measurement is performed at the landing site. Afterwards the rover moves to the other measurement points							
The cycle starts							
3	Drill	The rover drills	Drill unit, power, DHS, comms during the visibility windows (0.8 h)	All the rest of the payload, locomotion unit, navigation	30 min to 10 hours (1 day)	0.50	Depending on the soil
4	Night	The rover goes in sleeping mode	RHUs, power, DHS (only wake-up unit), comms during the visibility windows (0.8 h)	Payload, locomotion unit, navigation	14 hours	1.00	
5	Measurements	The rover measures the sample and transmit to the orbiter the data during the comms window	All payload (except drill), DHS, power, comms (only during windows)	Locomotion,navigation	1 day	1.50	Can be combined with the drill in case of short drill duration
6	Night	The rover goes in sleeping mode	RHUs, power, DHS (only wake-up unit), comms during the visibility windows (0.8 h)	Payload, locomotion unit, navigation	14 hours	2.00	
7	Moving	The rover moves at 100 m/h. To scroll for 2 Km 20 hours (2 days) are needed	Locomotion unit, navigation (initially and every 5 m), power, DHS, payload camera and computer (only few minutes), comms during the windows	Payload (except camera and computer)	2 days (10hX2,shorter phases are possible if the measurement points are closer)	3.00	Assumptions: max distance between measurement points: 2 Km, Part of the day with sufficient illumination: 10 hours. When the orbiter is visible (0.8 hours per day) the rover stops and transmits
8	Night	The rover goes in sleeping mode	RHU's,power, DHS (only wake-up unit), comms during the visibility windows	Payload, locomotion unit, navigation	2 nights (each of 14 hours duration)	4.00	
9	Comms	Additional 2 days are needed to download all the data volume required (TBC). The rover just waits for the comms windows and transmits during those	Power, DHS, payload camera and computer (only few minutes), comms during the windows	Payload (except camera and computer), locomotion unit, navigation	2 days	5.00	6 days in total are needed to send all the data volume to the Orbiter. This fixes the cycle duration
10	Night	The rover goes in sleeping mode	RHU's,power, DHS (only wake-up unit), comms during the visibility windows	Payload, locomotion unit, navigation	2 nights (each of 14 hours duration)	6.00	
End of one cycle							
Repeat the cycle up to 180 days (nominal endlife due to dust degradation)							

Table 2, ExoMars09 drilling cycle. [RD 2]

8.2 Locomotion requirements

Requirements on mobility are directly derived from the scientific requirements. The required distance between measurement points drives the design of the locomotion system and, in particular, its speed. This latter, in turn, together with the minimum number of measurements, drives the minimum time of presence on the surface needed to accomplish the scientific goal. According to [RD 2] minimum distance specified is 0.5

km, and maximum is 2 km, and number of samples is 10, which makes minimum travel distance 5 km, in case the system does not return to the lander at all, but acquires and sends the data autonomously. Maximum distance would be 20 km. A 100 m/h traveling speed would then call for 200 hours or 20 days traveling time, which is in line with anticipated 2-3 months life time, since traveling can take some 30% of total time, while the rest of the time is spent on communications, scientific measurements and sleeping over night. The requested traveling speed should be reached over a rocky surface described in the previous paragraph.

If robot swarms would be used locomotion distance can be reduced as the robots would be initially distributed over a large area. This way also locomotion speed can be reduced. Distribution of scientific instruments among several robots would add redundancy or also decrease size of the one robot. Added redundancy may allow acceptance of robot loss, which would relax obstacle overcoming capability and thus would allow smaller, lighter simpler and cheaper robots.

8.3 Scientific payload requirements

A recent initiative of the European Space Agency was concerned with the identification of specific objectives in the search for life on Mars. It aims to develop a set of imaging and spectroscopic systems which will facilitate a search for evidence of extinct microbial life at all scales down to 0.01 microns. These systems should also provide for the study of the mineralogy and petrography, as a function of depth, in the near subsurface region of Mars. Microfossils are most likely to be found in rocks that have been buried to a considerable depth and have resurfaced due to impact ejection or are exposed on canyon walls. The scientific instrument package is currently known as ‘the Pasteur package’.

The scientific objective of the Pasteur package is the search for signs of past and/or present life on Mars. To fulfill this mission, the package must be able to characterize the organic and inorganic composition of Martian deposits of exobiological interest. The package will be mounted on a rover, and must conduct measurements of multiple samples from surface rocks and the Martian subsurface. The Pasteur package is still at the conceptual design stage. However, some of the instrument components rely on previously developed payloads. [RD 2]

Recommended Analytical Instrument 'Pasteur' Package [RD 1, RD 2]	
Microscope: for examination of samples • 3 micron resolution • mass, 250-500 g • expected power, 3-6 W *Infrared spectroscopy*: molecular analysis of minerals and organics (with Raman) • expected mass, less than 1 kg • expected power, 3-4 W *Raman spectroscopy:* molecular analysis of minerals and organics (with IR) • expected mass, 1-1.5 kg • expected power, 2.5-3.5 W *Life marker chip:* Compare residues with known organic compounds • expected mass, 3 kg • expected power, 3-20 W	*APX-Spectrometer* (elemental analysis, detection limit: a few .1%) • mass, 570 g • power, 340 mW *Mössbauer:* quantitative analysis of Fe • mass, 500 g • power, 1.5 W *Pyr-GC-MS system:* isotopic, elemental, organic and inorganic molecular composition, and chirality measurements • total mass, 5.5 kg • power, 10-20 W *H_2O_2 and other oxidants dedicated sensors:* • expected mass, 100g
Drill and Sample Distribution System: This is an important feature of the Exobiology Package and will utilize various European technological developments in drills, moles, penetrations and sample distribution systems. • expected mass, 11 kg • expected power, 10-100 W	

Table 3, Recommended Analytical Instrument for 'Pasteur'-Package [RD 1]

The presented Pasteur-instrument package aims merely on search for signs of life from and below planet surface. Mass estimation has been done on the basis of realistic data for the instruments (already existing or in advanced design status): Instruments weight 32 kg. [RD 2]. The package is very large and may not be applicable for future novel locomotion methods that are designed merely to cover large distances and utilize quite limited local energy sources. A very large roving vehicle, walking machine or a balloon might be able to carry all these instruments, but a small flying, gliding or jumping instruments may adopt only some of these instruments. Alternative -smaller and less heavy- scientific instruments may include thermometers, gas analyzers, cameras, electrical resistance meters and other simple instruments to study atmospheric and surface properties.

Possible Analytical Instruments for 'Ariadna' Package	
Low-mass instruments: *Microscope:* for examination of samples • 3 micron resolution • Mass 250-500 g • Power 3-6 W *H_2O_2 and other oxidants dedicated sensors:* • expected mass, 100g *Wind speed measuring sensors* *Optical cameras with dedicated filters* *Thermometers* • Masses 10-100 g	Possible instruments with challenging mass: *Life marker chip* • Mass, 3 kg • Power 3-20 W *Panoramic camera* • Mass 2 kg • Power 8 W *Subsurface Electromagnetic Sounder* • 1.5 kg • 10 W *APX-Spectrometer* • Mass 570 g • Power 340 mW *Mössbauer:* quantitative analysis of Fe • Mass 500 g • Power 1.5 W *Rock surface drill:* A small surface drill, similar to one carried by the Beagle lander. • Mass 400 g • Power 2 W

Table 4, Possible Analytical Instruments for 'Ariadna'-Package

8.4 Household and auxiliary payload requirements

In addition to scientific instruments also a certain number of housekeeping, navigation, communication and power equipment are needed. The ExoMars09 CDF Study Report [RD 2] describes rover sub-system mass and energy requirements that are collected in table below.

Subsystem	Mass	Power
Communication system	6.3 kg	16.5 W
Solar Array	11.25 kg	
Power unit	2.15 kg	6 W
Data handling	4.4 kg	
Attitude control system	0.9 kg	
Harness	1.00 kg	
Battery	6.60 kg	
Thermal control	5.9 kg	

Table 5, ExoMars09 rover sub-system requirements [RD 2]

8.5 Energy requirements

As for power system solar panels, batteries and radio-thermal generators can be considered. Practically when considering novel systems, one should consider power generation methods that would utilize local power generation resources like wind or heat. Some of already consumed energy can be re-gained with novel solutions during atmospheric descent or rolling down the dynes, as for an example.

The ExoMars09 CDF Study Report [RD 2] presents a 6-wheeled 58 kg rover chassis, total mass with payload ~190 kg. Thermal control is realized with Radioisotope Heater Units and passive methods and does not call for external energy. The power budget for the rover is presented in following table.

Subsystem	Power
Navigation	10 W
Locomotion	30 W
Sensors for locomotion	5 W
Power system	6 W
Computers	12 W
Wake-up system	1 W
Communication	16.5 W
Scientific instruments	203 W

Table 6, ExoMars09 CDF rover power budget [RD 2]

The Ariadna rover can be assumed to have similar requirements for the household and communication systems, while locomotion, navigation and instrumentation needs will depend on selected architecture and scientific instruments. Further it is possible to switch between locomotion, science and communication phases so that the maximum power requirement will stay within reasonable limits. Thermal control will again depend a lot on selected architecture and passive methods should be preferred to save energy.

Subsystem	Power
Locomotion	0-30 W
Navigation	0-15 W
Household	19 W
Communication	17 W
Instruments	5-20 W
Thermal control	TBD

Table 7, Anticipated Ariadna rover energy budget

8.5.1 Energy philosophy

Independent from possible novel technologies for locomotion and power generation; communications, system control and instruments will need some electric power in every case.

> As an interesting exception on the statement above, one could imagine a completely passive research device that would travel carried by local energy sources (like wind), and would passively react on certain environmental parameters (temperature, humidity, air pressure, electric conductance) with the aid of smart materials (bi-metals, shape memory alloys, electro-actuated polymers). The materials that react on parameters would also participate directly to communication by passive means, like tilting a mirror or releasing a target.

However, if restricting to conventional communications and research instruments, a conclusion is, that some electricity will be needed.

With current technology mobility and guidance is most easily realized with electric actuators, which –however- consume a great deal of systems energy budget. If passive locomotion means could be adopted then less electrical energy would be needed and system size and mass may be reduced. Also alternative, possibly less efficient, energy production methods can be developed and utilized.

8.6 Folding for flight

As vehicle size and/or mass become higher, a question rises whether the launch system and lander system are capable to adopt it. One should aim towards systems that are low in weight and can be folded in a very small volume for the time of interplanetary flight.

8.7 Landing on Mars

The latest Mars-landers have relied on airbags, illustrated in image below. So far the airbags have been unnecessary and even harmful (if not successfully retracted) after landing. Mass and volume the airbags take is a penalty for the scientific instruments.

As an opposite approach the flexible gas-filled surface structure could function as a structural and active element for the roving vehicle. In that case no separate lander nor a separate landing system would be needed at all, which would save a significant amount of mass and volume, which has been also noted by the JPL Tumbleweed team [RD 11].

The image below, presenting the Pathfinder airbags, shows approximate size of the airbag needed to land 360 kg onto surface of Mars. This in turn gives a hint of a size of a flexible-structured Mars-rover that would not need a separate landing system at all. (Naturally, the heat shields, parachutes and retro-rockets are needed anyway.)

Figure 27, Mars Pathfinder airbag system in the Mars Yard at JPL.
Image: NASA/JPL / The Planetary Society. [RD 5]

8.8 Deployment

Before deployment any landing systems possible obstructing rover transfer from the land onto Mars surface (like remnants of airbag) are retracted or by other means removed form the rover's path. Driving ramps, if necessary, are lowered onto ground and surface conditions are checked for safe deployment. In case of integrated landing structure / rover structure none of these actions are necessary. Rover health and computer- and power systems are checked. Necessary aerials, cameras etc. are extended and deployed, after which the roving vehicle can either move onto surface or start making scientific measurements immediately.

9 Biologically inspired locomotion concepts

When considering the past and planned robotic missions, quite often a biological inspiration can be recognized, -except for the wheeled vehicles; The Phobos hopper imitates locomotion of a grasshopper or a flea, Soviet Mars 2 and Mars 3 –crawlers move in a similar manner as seals on dry ground, Pluto digs into ground like a mole or a earthworm, origin of the JPL Tumbleweed is clear, airborne balloons resemble soap bubbles, and swarms duplicate spreading of dandelion seeds. As an exemption to wheeled devices in general, the Russian Marsokhod rover possesses a biologically inspired locomotion sequence where it can move by extending and retracting its body in a similar manner to an inchworm.

9.1 Russian Thistle

The robotic tumbleweed would imitate a natural tumbleweed and would travel along Martian surface driven by the wind or by it's internal motor, or rolling down the slopes. The robotic tumbleweed might also have a possiblity to jump over some obstacles.

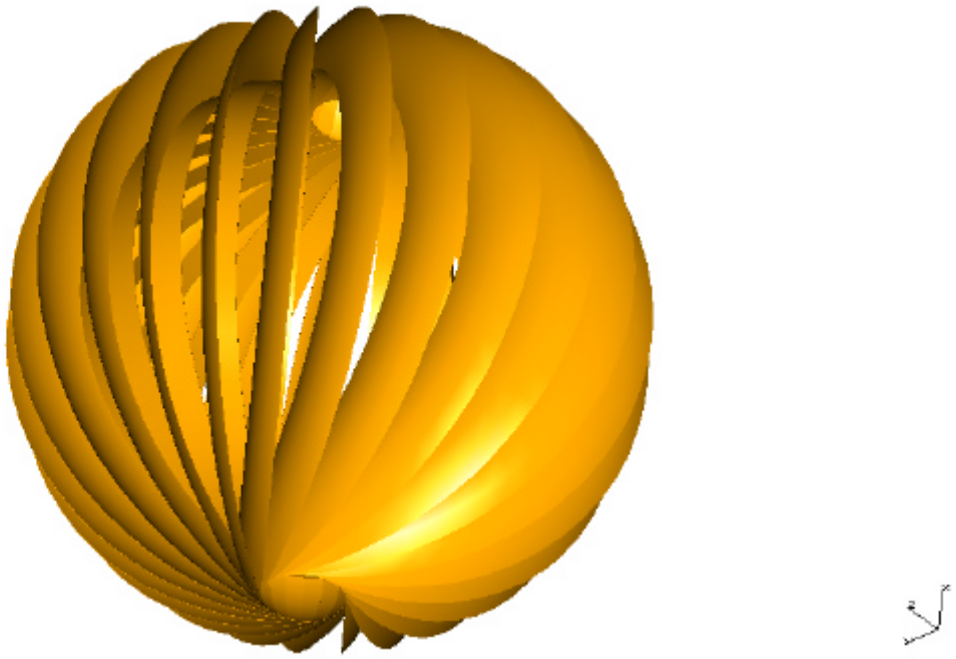


Figure 28, An artistic view of a Robotic Tumbleweed

9.2 Grasshopper

Mechanical models of a grasshopper are already being studied in many occasions all around the world. In most cases the hopper appears to be quite small and thus its payload capability is quite limited. However, hopping capability of the hopper often exeeds as much as tens of times the size of the hopper; both in vertical and in horizontal direction.

9.2.1 A fuel-operated hopper

The hopping robots, developed at the Sandia National Laboratories, use combustion-driven pistons to make leaps as high as 20 feet. Hydrocarbon fuels provide greater energy densities than batteries, a small combustion-powered hopper theoretically can travel greater distances and clear larger obstacles.

The Sandia hopping robot is contained inside a grapefruit-sized plastic shell that rights itself after each jump. A pre-programmed microprocessor inside the hopper reads an internal compass, and a gimbal mechanism rotates the offset-weighted internal workings so that the hopper rolls around until it is pointed in the desired direction. The hopper jumps about 3 feet in the air and 6 feet from its starting point on each jump and, theoretically, could last about 4,000 hops on a single tank of gas, which is about 20 grams of fuel. Each hopping cycle is about 5 seconds. Another hopper, about the size of a coffee

can, jumps 10 to 20 feet in the air and theoretically could go 100 hops on a tank of fuel. [RD 35]

Figure 29, Sandia National Laboratories fuel powered hopper [RD 35]

9.2.2 A miniature hopper

A single-actuator hopping robot, developed at NASA JPL, is capable of moving a camera and a small science package by jumping. A single actuator is enough to propel, steer, and self-right a simple hopper. The same actuator can also pan an on-board camera as well as manage a science package. The entire system weighs less than 1.5 kg. The robot includes a foot, a bearing on the foot, and a tilted assembly that contains the rest of the robot. The tilted assembly includes an extendable leg that contains a spring and an associated linkage for extending and retracting the leg. To store energy for the next hop, the motor drives a power screw that compresses the spring and retracts the leg. At the desired moment of hopping, the motor actuates a mechanism that releases the spring, which then rapidly extends the leg to generate the hopping motion. The spring and linkage are designed together to make the extension force a nonlinear function of displacement that maximizes the proportion of spring-compression energy converted to hopping kinetic energy. Because the robot can be expected to lie toppled over after most hops, a self-righting mechanism is included. [RD 36]

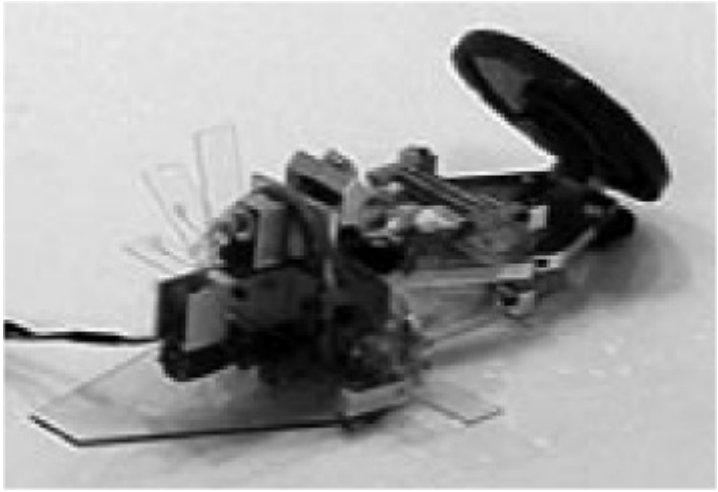


Figure 30, A single-motor actuated hopper. [RD 36]

9.3 Robot swarms

No matter how sophisticated the developed locomotion system is, if it breaks down or the robot gets stuck, the whole mission is over. The only real way to overcome this problem is to use multiple robots instead of a single one. Redundancy is extremely important for robotic systems exploring foreign planets and is the main reason (along with the increased mobility) why a short presentation of multi-robot systems (here swarms) has been included to this study.

9.3.1 Background in nature

The multi-robot approach fits well in the scope of the biologically inspired research at hand, because the nature is full of systems where instead of having one large unit with superior mobility (or intelligence), the natural environment has created systems where this mobility (or intelligence) has been distributed over many small (or simple) units.

These systems include for example insect societies, which are highly redundant and able to survive in changing and sometimes even hostile environments. “Go to the ant, you lazybones, consider its ways and be wise” (Bible, Proverbs 6:6) indicates clearly, that the incredible work done by these little creatures has been known for thousands of years. In spite of their low level of intelligence they have survived evolution’s competition. These animals form seemingly chaotic structures, societies, that when studied more closely, show a high level of distributed intelligence. Their ability to survive comes from the high redundancy and structure of the society. Ant societies have several fascinating features, such as chemical and tactical communication, asyncrohonicity, self-organization,

coordinated behaviors, self-activation, stability, and so on. See [RD 41] for extensive presentation.

9.3.2 Definition of the term swarm

The word swarm has no exact definition in the robotics literature. In [RD 42] it stands for the whole society. [RD 43] uses the word in an analogue way with the nature, i.e., a swarm is a group of small autonomous agents, that will come together in order to be able to accomplish a task that would be impossible for them to do alone. The definition by [RD 44] sums them all up nicely: "A swarm is a set of (mobile) agents which are liable to communicate directly or indirectly (by acting on their local environment) with each other, and which collectively carry out a distributed problem solving. In this sense we refer to functional self-organization, since this emerges from the swarm's internal dynamics and its interaction with the environment. The swarm functioning induces both the genesis of functional collective patterns which characterize the differentiation and spatial-temporal organization of the agents of the swarm and also the parallel organization of the material elements in the environment upon which each agent acts."

A swarm can be homogeneous or heterogeneous. Robots can be physically identical (i.e. similar sensors, actuators, etc.) but are still considered heterogeneous due to the different behaviors. The composition of a swarm has direct linkage to the control solutions; some kind of distributed control has been used normally with a homogeneous case, while a heterogeneous swarm is usually controlled with some degree of centralized control. This kind of division is actually quite natural. In a homogeneous case all the members are alike and the system can easily be understood to work in a parallel way. In a heterogeneous swarm more complex control solutions are needed.

Homogeneous swarms are in principle more flexible. They continue to operate even though some of the members in the swarm "die". In a heterogeneous case death of an agent can be fatal for the function of the whole swarm. Another benefit which a homogenous swarm has is that the behavior of an agent is predictable to the other members of the swarm, which decreases the need for an active communication. The use of a heterogeneous swarm, on the other hand, makes it possible to give the system more complicated tasks, because different groups can be designed to perform certain sub-tasks. It reduces the overall complexity of individual members.

9.3.3 Benefits

[RD 45] lists several general advantages of distributed autonomous robotic systems. These include simplicity, modularity, load variance, cooperative and coordinate abilities, exchangeability, variety, response ability, mutual diagnosis and miniaturization. Simplicity comes from the decomposition of the system into a number of elementary units. These units are robotic units with simple functions. Modularity provides opportunities to easily vary the composition of the system. Load variance provides fault

tolerance and reduction of load. Cooperative and coordinate abilities improve the ability to carry out the required tasks. Exchangeability is based on the modularity of the system and provides flexibility, fast response and fault tolerance to the system. Variety is related to the configuration of the system. It is based on the behavioral repertoire of the elementary units, i.e., the simpler the units and the more difficult the task, the more units that can be used for the completion of the task. The response ability is naturally increased based on the multiple functional elements in the system. Mutual diagnosis benefits from the self-diagnosis of the elementary units. Miniaturization is based on the simplicity of the elementary units and modularity of the system.

9.3.3.1 Higher redundancy

The redundancy of a swarm is superior compared to a single robot solution, even though this robot would have much more intelligence than the members of the swarm. A malfunction in a single mobile robot on Mars can be fatal, whereas the same happening in a swarm would only decrease the performance. In some cases the information gathered by a robot in trouble (stucked), could be saved by transmitting it to another robot nearby (that is, if the direct transmission to the lander is not possible). In some rather wild scenarios, two or more robots could actually help a robot to get out of a hole by giving a “helping hand”.

9.3.3.2 Increased mobility

As the topic of this study is to provide some biologically inspired solutions for robotic surface mobility, it should be addressed separately also in here. If the target of a planetary mission is to obtain as much information as possible about some particular area with normal lander transportation constraints (size and mass of the payload) we have basically two possible ways to do it: to design a locomotion system for a single specialized robot or to design a swarm of smaller and lighter robots.

Even though the single robot will be bigger, it will not necessary be faster or able to go over larger obstacles. The main reason for that is the non-excisting fault tolerance. Each movement must be well pre-planned and is based on the research done by the flight control crew on Earth. This will naturally take some time. With a swarm system, more autonomy can be given to the units. This is of course due to the above mentioned high redundancy. This results directly to faster movements and thus better mission area coverage. A small size (payload volume must be splitted into several parts) is in general a negative feature for successful locomotion in rough terrain. However, when considering the undeniable success of the ants, one has to agree, that size isn’t everything. In several studies the self-organizational and self-reconfigurable features of social insects (e.g., ants building living bridges over water ways) have been successfully transferred to multi-robot systems. Robots have been made to help other robots to overcome obstacles that are too large or tall for single robot to pass on their own. Similar features would be very

valuable also on planetary exploration missions with swarm robotics. On the other hand, a small size can even be a real asset when narrow passages between obstacles (or holes, gaps, etc.) must be used in order to proceed to the next working area.

9.3.4 Some proposed scenarios

There are numerous studies conducted in the field of multi-robot systems over the past ten years or so. However, only a small portion of them can be directly linked to planetary exploration issues. Out of those two interesting cases are shortly presented here.

9.3.5 Augmenting a large rover

[RD 46] presented in their paper a scenario where the redundancy of a single large rover was increased by including some small potentially disposable robotic units to its payload. After reaching some interesting area, these smaller units would be released and they would start their own research missions. The larger unit could operate as a recharging and long-range communication station for the smaller units. It could also include some sophisticated sensors for example soil example studies. Later, this kind of mother-children(swarm) relationship type robots were named as marsupial robots, see for example [RD 47].

9.3.6 Large-scale systems consisting of small and simple sensor-like robots

Today, when we are capable of manufacturing very small robots with multiple sensors and actuators, there is a need to tackle issues related to the use and control of a large scale robotic systems (i.e., large swarms). (Brooks and Flynn 1989) presented already in their excellent paper some possible scenarios for large-scale robotic systems (small and simple units). Distributed over a large area (dropped from the orbiter or from the lander into the winds) these simple robots could for example look for certain compound and if successful they would reveal a reflector for orbiter to detect. The development of micro and nano technology will give even more possibilities for these large-scale systems in the future.

9.4 Off-loaded walker

In order to realize low-mass, low-power walking system effect of the walker body weight should be reduced in a similar manner as for marine animals crawling on the sea bottom. On Mars off-loading most propably would happen with the aid of a balloon. Due to low density of Martian atmosphere the size of the balloon would be significant; much larger than the walker itself. Due to large size of the balloon it is also subjected to Martian

winds, that may become quite strong at some times, as is well understood. Thus presence of the off-loading balloon may reduce reliability of the walker.

9.5 Selection of locomotion concept

The several presented locomotion concepts all have their benefits and weaknesses for planetary exploration. In this study we concentrate on development of a Russian Thistle type rover. The Thistle has an apparent capability to utilize local energy source –wind- and it easily can be scaled up or down into desired size. There also exist experimental data on similar JPL Tumbleweed, and motorized robotic balls studied at the Helsinki University of Technology. Combining these experimental results may reveal new views, ideas and solutions.

9.6 Motivation

As several six-wheeled vehicles have already been exploring Mars surface, a short discussion on motivation of a ball-shaped roving vehicle is justified.

The main goal on Thistle development is to at least partly utilize local energy sources (wind or heat) for locomotion. Direct wind propulsion on a wind-borne ball appears to be the most simple and efficient method to utilize local energy sources. Locomotion of the Thistle is aimed to be autonomous and mostly lacking any kind of external control or guidance, and goal is to cover a long distance during a lengthty time.

Diameter of the ball exceeds wheel diameter of a four or six-wheeled rover of a similar mass. Although body structure of the rover allows overcoming obstacles whose height exceeds the wheel diameter (while the ball can only overcome obstacles smaller than 50% of ball diameter), energy efficiency of a large sphere on smooth terrain is propably better than that for a small-wheeled rover.

In this sense the Thistle is not to replace roving vehicles that travel accurately short distances to desired destinations, but the Thistle is to be dropped on surface and then autonomously cover a long distance with locally available energy.

10 Local energy sources

Rover power-supply sub-systems play a significant role in rover mass and lifetime. Lately solar cells and batteries has been used in conjunction, while older Viking landers – as for an example, and some future designs rely on Radio-isotope thermal generators (RTG). Some old rovers were even tethered to the lander. Especially batteries and solar cells suffer from limited life and harsh environmental conditions.

Utilization of local energy sources that would free the rover from batteries would provide the rover better autonomy and possibly a longer life time and operation range.

Local energy sources on Mars could be direct solar electricity, thermal energy and wind power, -all originating from Sun radiation. Direct solar electricity is already familiar and its limitations are known. So far wind-energy has been studied, and some prototypes have been operating on Earth. Utilization of thermal energy has not been apparent up to date on roving vehicles, while some passive temperature control systems use it. Energy sources not listed yet might include chemical energy stored in Martian soil or atmosphere, and potential energy of slopes and hills (however, one needs first to get on top of the hill), or potential energy of the lander while still at the orbit. How could we store the huge amount of energy that is wasted into atmosphere in the form of heat during spacecraft descent and landing? Abundance of carbon dioxide and solar radiation opens an interesting possibility to utilize biological photosynthesis for energy production.

10.1 Wind

Martian wind is in the public probably the best-known phenomenom of planet Mars. Atmospheric density on Mars surface is very small, only 1.6% of that on Earth. However, despite of low density, high wind speeds carry a significant amount of energy. Theoretical energy content may be calculated by the speed and mass flowing through a defined area. The area could be defined by diameter of a windmill, as for an example. The table below presents energy content of wind flowing through three different areas at two different speeds. Maximum collected energy is limited by Betz-limit to approximate 60% and real windmills on Earth operate at 40% or 20% efficiency depending on rotor type. [RD 17]

Air density: r = 0.02 kg/m3 **Kinetic power: P = dE/dt = 0.5 x r x p x R^2 x v^3**		
Generator diameter 2R (m)	**Wind speed v (m/s)**	**Kinetic power P (W)**
1	**7**	**2.7**
6	**7**	**97**
30	**7**	**2 423**
1	**30**	**212**
6	**30**	**7 630**
30	**30**	**190 755**

Table 8, Energy content of Martian wind.

Since household energy requirement alone has been estimated to be around 20W, and in addition is needed either locomotion, communication or science power; -if not them all

simultaneously. Peak power will then be around 40-50W, some of which may be, however, drawn from a temporary storage like batteries. Average power generation should then be around 30-50 W, which indicates at 40% efficiency a 70-125 W kinetic wind power. A 6-meter windmill operates in this range during reasonable Martian wind conditions.

In addition to windmills the energy of wind can be utilized also in some other ways. One method could be to generate drag-force with a kite or sails, or let the wind push a ball like a Russian Thistle; -just to mention a few options.

10.1.1 Wind mills

Windmills for a large-scale Martian energy production, in the range of kilowatts and hundreds of kilowatts, has been studied widely already, as for an example in [RD 17]. These cannot be considered as a solution for mobile roving systems, but only for stationary power plants.

However, a small-scale windmill designed for a rover power-source was presented in [RD 23]. Here a 1-m diameter windmill was considered for a Venusian rover (atmospheric density 64 kg/m^3). Expected collected windmill power was 1.8-15 W at 0.5-1 m/s wind speed. Corresponding power on Mars with Martian atmospheric density and wind speeds 10-30 m/s would be 4.7-127 W.

The windmill power was utilized in two ways; either the windmill was mechanically connected directly to driving wheels (with sufficient gear ratio) and the mill practically drove the rover. There is also possibility to collect surplus wind energy with a generator and store it in batteries. An alternative method is to use the mill power to charge batteries and drive the rover with electric motors, which provides easier control and more simple mechanical solution.

Figure 31, A wind-mill powered rover. (RCL-company)

A drawback of using a windmill for a novel biologically inspired roving system is that the mill needs a proper alignment and a steady base to be operative. A large six-wheeled rover can provide this platform, but any kind of hopping or rolling devices may not be suitable solutions.

10.1.2 Direct propulsion – A Russian Thistle

Direct wind propulsion here means, that the kinetic momentum of moving air mass directly and without any energy conversion or transfer mechanisms causes the rover to move. One example is the Russian Thistle that is blown forward by the wind. Alternative solutions cold use sails, kites and wings, which –thanks to aerodynamics- in principle can provide traveling velocities exceeding the wind speed.

The Russian Thistle appears very attractive due to its simple structure and mobility concept. A similar Tumbleweed-design has been studied closely in JPL [RD 11]. The following sections present an analytical study on expected traction force on Russian Thistle placed on Martian surface. In addition effect of re-shaping the Thistle surface to imitate a wind-turbine is discussed.

The tangential blades associated with the wind-turbine–like layout may have also several other functions to assist Thistle motion on surface. The blades add ball diameter and they add flexibility, -both features assist in overcoming obstacles. The blades may also collect some wind-borne sand that causes an off-balance that makes the ball to rotate. The sand falls back onto ground as the ball rotates.

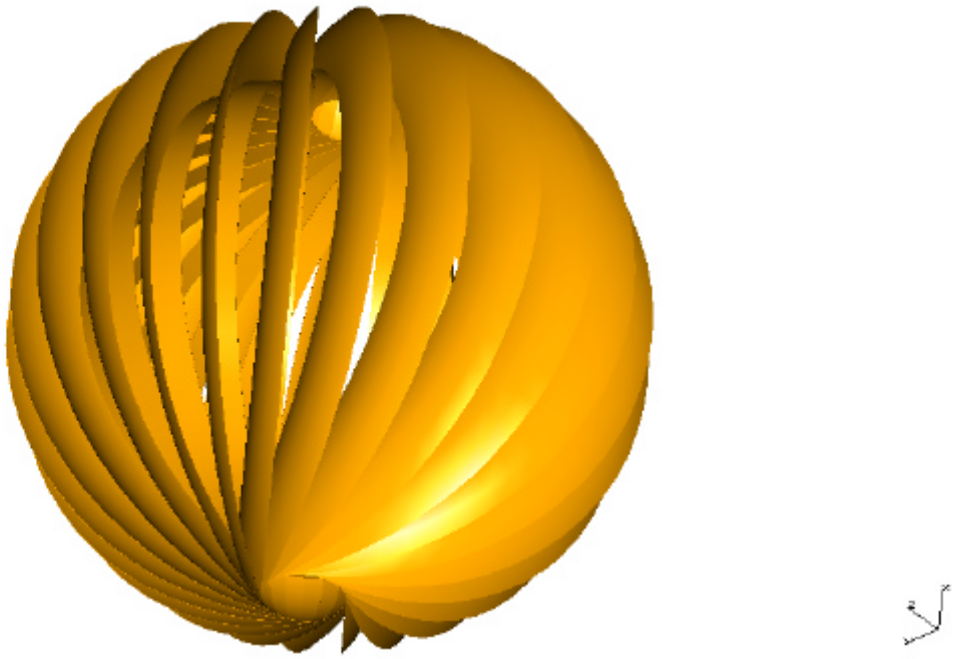


Figure 32, An artistic view of a Robotic Russian Thistle with a wind-turbine layout

10.1.2.1 Force and moment analysis

The correct and complete static and dynamic force / moment analysis can be carried out on the authentic geometrical and dynamical model of the construction by computational fluid mechanics programs. The calculation will include the geometric model of the rover, its environmental placement, the dynamical model of the rover, the friction coefficients with the environment, condition of rover contact with the soil and obstacle, interaction of the moving air with the blades on the rover in both static and dynamic cases.

Such investigation can be carried out on dedicated software. Commercial software usually can provide many parts of the above analysis individually, but prêt-à-porter integrated simulation of the above scenario is not the purpose of any consume mathematical modeling software.

In practice, the validation of the above scenario is accomplished via engineering approach: the preliminary design carried out by the basic engineering considerations in static cases, later elaborated by the dynamic and control model, then a scaled and full scale mock up proves the operation principles, and finally optimization improves the performance. Hereby we follow this very approach and deal with the first thing first. The

viability of the rover is determined by the basic design; any optimization cannot improve the design substantially and will always be hindered by the huge uncertainty of the various physical and operational factors of the rover.

The design shall be justified by the robustness of the bio-mimetic design principle rather than the rover's particular parameters. However the fundamental engineering analysis is indispensable.

10.1.2.1.1 The geometrical model

The rover is considered as a sphere, where various aspect of the force/moment analysis would add certain consideration to its physical or geometrical character – on the course of the analysis. It should be again stressed that these characters are highly hypothetical and their selection serves a qualitative analysis rather than a quantitative one.

10.1.2.1.2 Action forces

The rover is affected by a single active force $F = kArv^2$, due to the motion of the air, which is analyzed in this section. The force acted upon the sphere is due to the drag of air which is a function of the shape. It is difficult to estimate the drag coefficient without knowing the actual design. It could be however easily predict by FCM program or by scaled experiment in a wind tunnel – having the approximate profile of the rover. Hereby we give an estimate, but at the same time we always keep in mind a huge error margin for making any pragmatic conclusions.

The drag coefficient *k* is taken to *k=0.8*, on the following basis. For the smooth sphere *k=0.4*, and *k=1.2* for the concave half shell. Since the rover will not be smooth at all, but will not be capture the full strength of the wind either, we take *k=0.8*, which is even less than the *k=1*, for the circle plane. (These coefficients vary slightly with the sources.) The following figures will show the drag forces for various *k*, and *A* –area of cross section. The air density ? can be taken for ? =0.02 kg/m^3 for Mars, and ? =1.29 kg/m3 for the air on Earth. The following diagrams give qualitative picture for these forces on the Mars as well as it shows these forces for the NASA Tumbleweed on the Earth. If the latter analysis is plausible the qualitative image for the Mars will be too.

The drag on the NASA Tumbleweed is shown here.

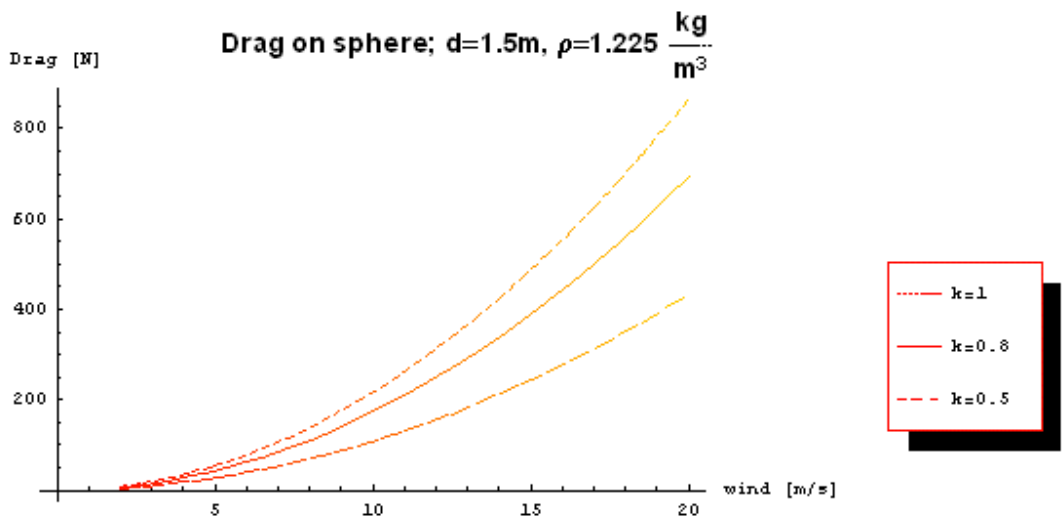


Figure 33, Calculated drag on the NASA Tumbleweed on Earth.

Note the dominant factor of the wind speed and a minor factor of the shape factor. The ~20 kp force on the 12 m/s wind and a lessen k~0.5 can move the ball with a relatively high speed.

From the formula of the drag force $F = kArv^2$ it can be seen that the equivalent aerodynamic situation can be modeled on Earth if we scale down the diameter of the ball to account the ratio $r_E / r_M = 1.225/0.02 \approx 61$ of the air density on the Mars and the Earth, as much as the Fr moment acting on the ball would be the same on both environment. Thus $\sqrt[3]{61} \approx 4$, would give the necessary $6/4 = 1.5$ [m] diameter aerodynamically equivalent ball shape of the NASA Tumbleweed, to model the thought 6m diameter robot on Mars. Since the earthly piece is working, the rest of the section is aimed at getting some quantitative insight of the task.

It can be seen that drag itself is quite small on the Mars, even though it will be compensated by a larger arm of this force. A hypothetical 6m diameter ball experiencing a ~5 kp drag force at 10 m/s wind. With a 7 m/s high day time wind the drag is ~2 kp, which is not enough to move the ball. At 20/ms high speed storm the drag is ~15 kp, which is felt to be not enough to move the ball.

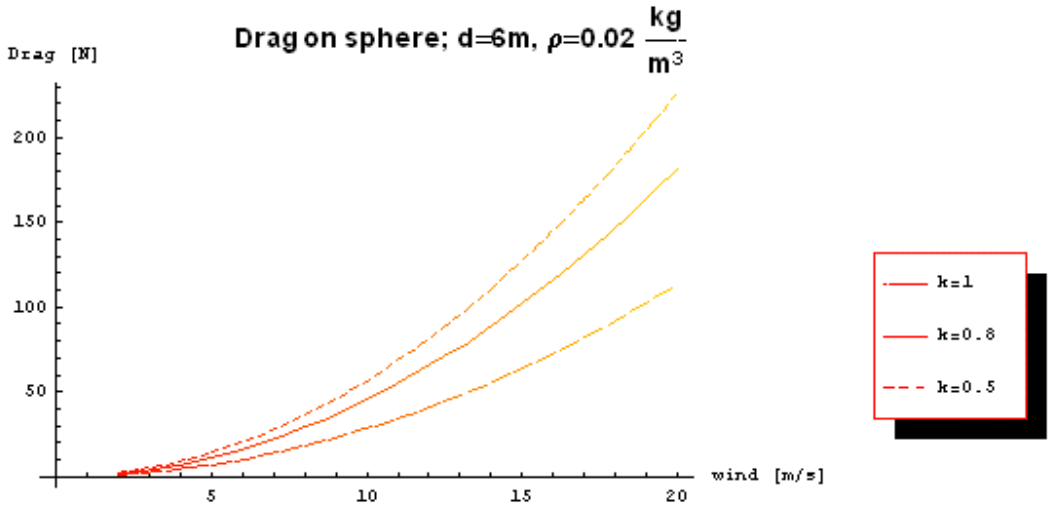


Figure 34, Drag on a 6-m Tumbleweed on Mars.

An essential feature of the proposed rover is that it contains blades on its surface. Its effect will be taken account based on a turbine principle. It will be seen whether such attachments can positively affect the total driving force acting upon the sphere. Since we don't have the real constructional model of the rover, we take into account these factors partially. One concentrated force will be added, which is acting on the upper most blade of those attached on the sphere. This is a conservative and realistic estimate. The shapes of the rest of the blades are such that they contribute to the drag force only. This force and the above force however exert a moment upon the sphere, which should be considered when dealing with the motion of the ball. This will be employed in the next section.

From the various turbine models, the Pelton-turbine is applicable here. The impulse force of moving air acting upon the blade is calculated as:

$$I = rAv^2$$

, where A is the cross section area of the blade. Considering a *single* blade which is 20 cm wide and circularly assembled on the quarter part of the 6m diameter sphere, the impulse force is shown here (with various coarse approximations).

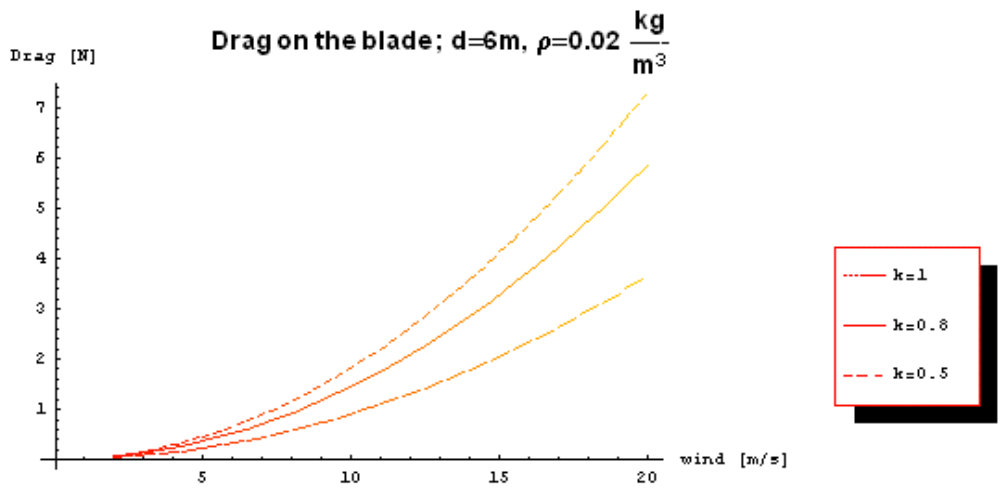


Figure 35, Drag on a turbine wheel blade on Mars.

It can be seen that this force is a diminishing value. However any force would move the sphere if the resistance to the rolling is small enough. This is investigated in the following. Albeit the blades help the rover move at a smaller wind speed it bears other essential functions as discussed in the energy production section.

10.1.2.1.3 Friction at rolling

The rolling friction in essence a continuous overcoming of small obstacles arising as a result of penetrating the rover into the soil. With this is mind, we can deal with bigger obstacles like the scattered rocks on the surface on the Mars.

To proceed consider the force/moment balance of the sphere in the figure below. The motion (instantaneous rolling) is possible if the moment of the action forces F are bigger than those required for the static moment equilibrium:

$$Fr - Gk = 0$$

Fr however is a composite moment M due to the air movement acting on the whole surface of the rover, and can be calculated as above shown. If the ever-present rock scatter is taken into account, than the arm of the F force will be noticeably less than r, so the moment M is calculated accordingly. In dynamic case, the force F will be bigger when the rover collides with a small rock, which facilitates to overcome bigger rocks.

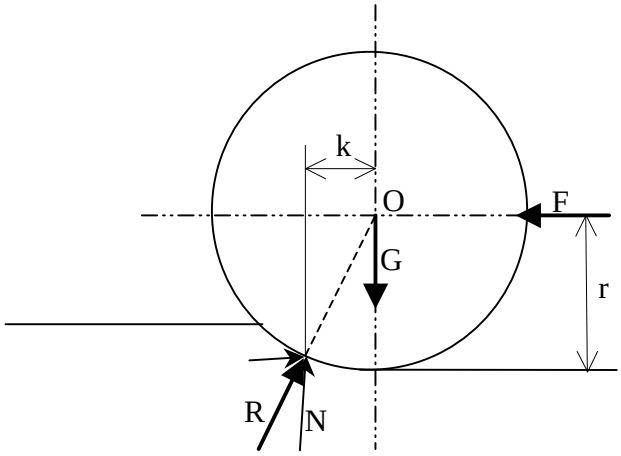


Figure 36, Forces acting on ball when rolling.

In an exemplar case, consider a 6m diameter ball with about 1m arm of force of resistance to rolling (*k*). It is about 20 degree of attack angle of R toward center of the ball. Geometrically means that the ball should overcome a 17cm height obstacle to move from rest. Having a 50 kg mass ball and 3.72 m/s^2 gravitational acceleration a moment of 186 Nm needed to be bring into motion the ball. Once in motion the moment could be less to keep it in motion. Considering the terrain assumption this could give a continuous motion on the typical surface on the Mars with scattered small rocks and minor slopes. Note, that aerodynamically equivalent ball, is acting in a lesser gravitational field, which makes the experiment on the Earth dynamically more demanding.

This moment can be generated, taken into account the force/moment analysis above. The drag force on the sphere is not enough to generate that moment in general, as shown in the following diagram.

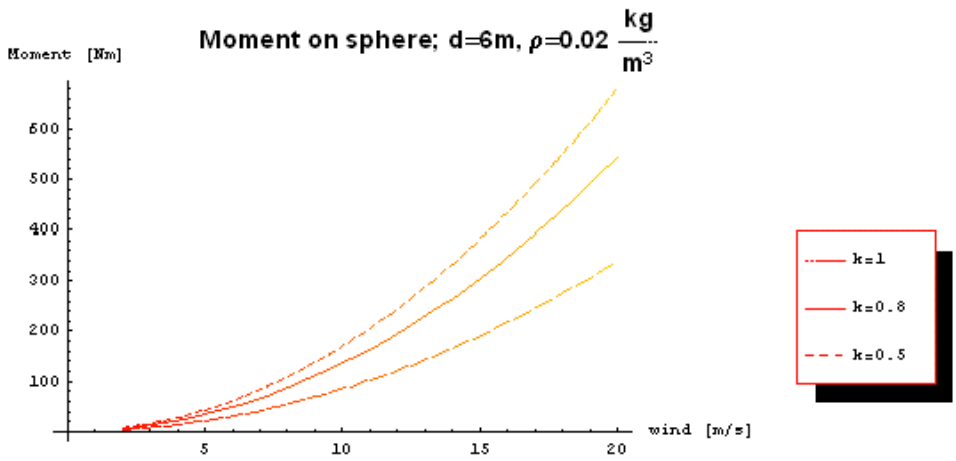


Figure 37, Moment on 6-m sphere on Mars.

The moment could be enough when there is a storm like wind. At lower wind speed, additional instruments are needed to move the sphere.

The moment generated with the Earth air on the NASA Tumbleweed is the same as for the 6m diameter sphere since the diameter was scaled so that to compensate the ratio between the air density.

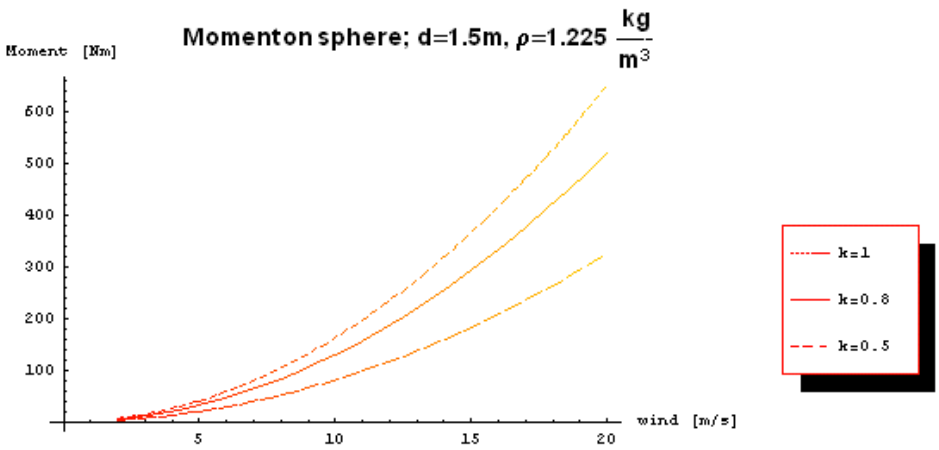


Figure 38, Moment on 1.5-m sphere on Mars.

Investigating (with some approximations) the case for 7 m/s the additional blades may generate the necessary trust. One blade generates 4 Nm, which can be doubled for the reaction forces on the blade and calculating for the 10 upper most blades makes 80 Nm. The 80 Nm drag on the sphere and the 80 Nm on the blades wouldn't enough to move the sphere. This diagram shown below.

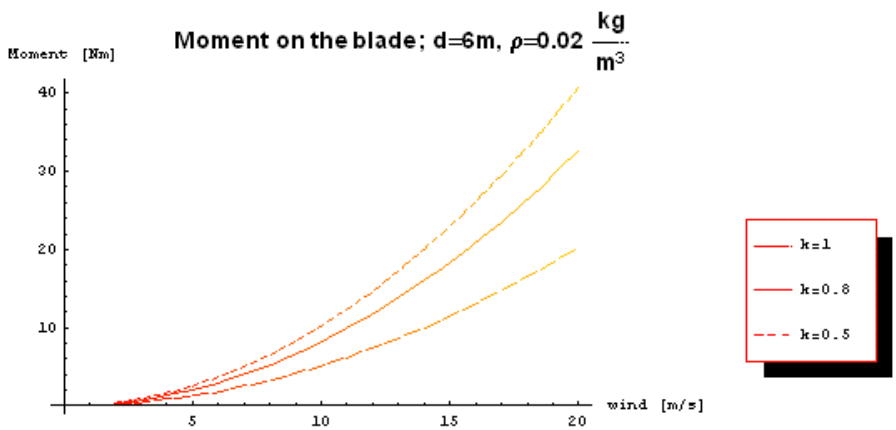


Figure 39, Moment on turbine blade on Mars.

At 10 m/s wind the following reasoning gives, 160 Nm and 40 Nm which together is enough to move the sphere. At such conditions, it can be said that a higher than the daily wind would bring the sphere into motion. This property however would be notably fortunate, if we aim to change locations at a rarer occurred high speed (>10 m/s), and wish to stay at the spot on a normal daily wind movements (~ 7 m/s) – without any additional technical measures.

10.1.2.1.4 Effect of spikes

Further improvement in efficiency can be achieved by modifying the design, adding spikes into the sphere. This would have the following effects: obstacle overcoming capacity, decreasing the moment of the rolling resistance – lessening the moment needed to move the sphere, using the spikes' passive movement (balanced with springs) for energy production.

Figure 40, A natural spiked Thistle.

The figure below left illustrates how a passive Spiked Thistle with spring loaded spikes adapts to surface geometry. With properly dimensioned spikes also obstacle overcoming capacity can be enchanced. If the Thistle would be propelled by wind, some linear generators (magnet and coil) in the spikes could be used to produce energy. The illustration on the right shows how an epicentric rotating mechanism extends the spikes in a sequential manner and thus makes the Thistle to roll actively. The spikes could be activated also with some other means, like air or hydraulic pressure or linear motors. If heat energy could be guided in a controlled manner from Thistle surface to the individual

spikes then bi-metals, shape memory alloys or linear wax actuators (based on melting and expansion of wax) could be used to produce motion from local energy sources.

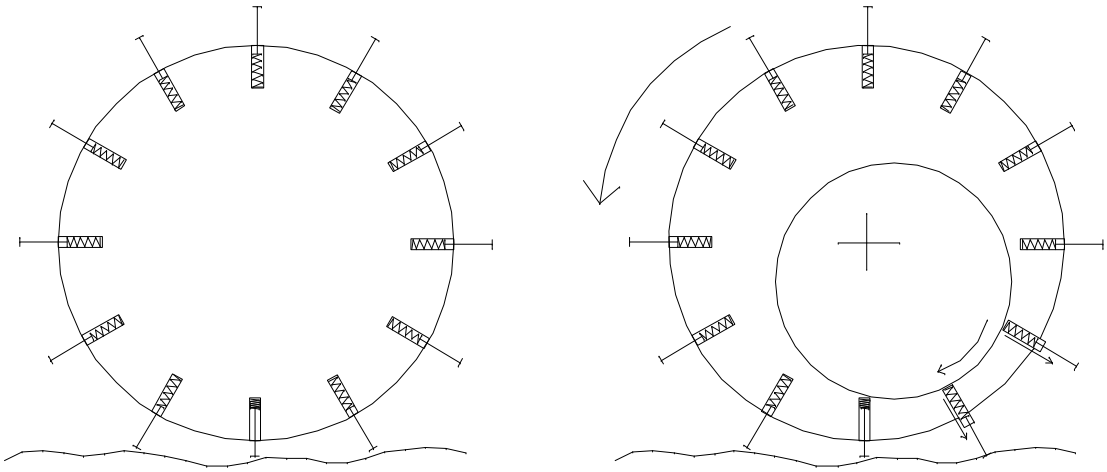


Figure 41, A passive (left) and an active (right) Spiked Thistle.

10.1.3 Test setup

In order to experimentally compare performance of a turbine-type ball with respect to a plain ball a simple test set-up was constructed. The test-items were two 32-cm beach balls, one of which was equipped with turbine blades or pockets. Six pockets were constructed of plastic sheet and taped on surface of the ball. Pocket height was 35 mm at maximum, and zero at poles.

Plastic poles with pin-holes were glued on balls to provide a support point and rotation axis. The ball was then assembled on a pivoted jig. The jig was supported by an electronic letter scale that allows read-out of force acting on the ball. The turbine ball pole was also equipped with a short lever arm (55 mm long) and a pice of thread and counter-weight, which with a properly positioned letter scale allowed measurement of torque acting on the ball.

Wind load was generated with two parallel-mounted blowers. Intensity of wind was varied by adjusting power input of the blower, and also by selecting two different distances from the blower (0.83 and 1.66 m). Actual wind speed and wind profile was measured on both locations with an electronic wind speed metering device.

The images below present the balls and complete test set-up.

Figure 42, Test set-up for a comparative wind force measurement.

Test set-up properties		
Test ball diameter	320	mm
Turbine pocket height	35	mm (in center line, zero at poles)
Turbine pocket cross-section area	8797	mm2
Number of pockets	6	
Ball cross-section area	80424	mm2
Single pocket area/ball area	0.11	
drag force / scale readout ratio	2.22	(mechanical amplification of support system)
Torque arm length	54	mm (to measure turbine torque)
Read-out accuracy	10	Gramms (scale read-out variation)
Scaled read-out accuracy	0.22	N (drag force variation)

Table 9, Some properties of test set-up.

The wind velocity was measured at free-flowing arrangement (without ball or fixture) with a hand-held wind-speed-meter. The speed was measured at two different distances,

with three blower power levels and at three different heights (ball lower edge, middle height and ball upper edge). The results indicate one clearly unsuccessful speed measurement (circled in table) that causes an undesired peak in graphical presentations. Reason for the inaccurate result is that blower levels 2 and 3 happened to be so close to each other that wind velocity difference was lost in read-out accuracy. The same applies in measured drag force.

	Measured wind velocity (m/s)					
Distance from blower (m)	**0.83**			**1.66**		
Measurement height (mm)	**160**	**320**	**480**	**160**	**320**	**480**
Blower setting						
Level 1	3.2	3.7	3.4	2.6	2.4	2.1
Level 2	3.5	4.6	4	3.2	3.2	2.6
Level 3	4	4.6	4.1	3.2	3	2.6

Table 10, Wind velocity measurement.

The graph below presents the wind-velocity vertical profile. Maximum velocity affecting in the middle of the ball was used in the following calculations.

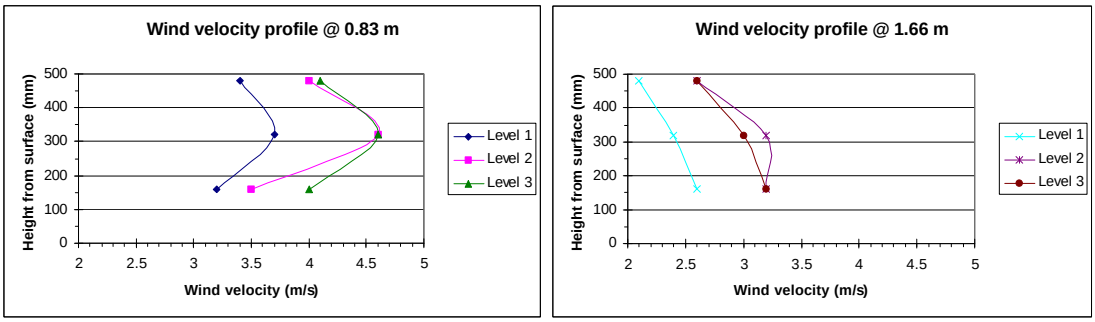


Figure 43, Measured wind velocity profile.

10.1.4 Test results

The test was run with three different blower power setting and at two different distance from the blower. The table below shows the results. In close distance (0.83 m, high wind velocity) the turbine ball appears to generate 66% higher thrust than the one without turbine pockets. In larger distance (1.66m, low wind velocity) the benefit of the turbine lay-out appears even more favorable exceeding 70%. Resulting torque on the turbine ball appears quite low; if the torque is translated as an point-load on a single turbine blade, the theoretical wind force (0.19 N) on the blade is only 7.2% of total push force (2.6 N at Level 3, 0.83 m distance).

			Measured drag force (N)				Measured torque (mNm)	
			Turbine ball		Round ball		Turbine ball	
Distance from blower			0.83	1.66	0.83	1.66	0.83	1.66
Blower setting	Measured wind speed							
	@0.83m	@1.66m						
Level 1	3.7	2.4	0.58	0.27	0.35	0.15	4.24	17.48
Level 2	4.6	3.2	1.06	0.49	0.64	0.27	9.54	30.72
Level 3	4.6	3	1.10	0.53	0.66	0.30	9.54	30.72

Table 11, Test results.

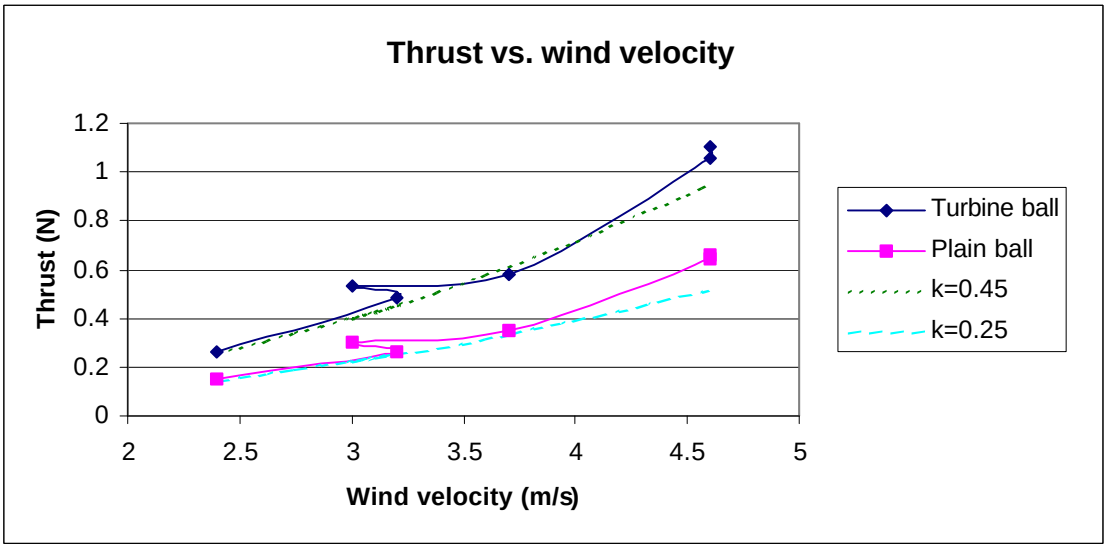


Figure 44, Test results graphical presentation.
(Note the peak resulting from a measurement error.)

The graphs above presents also analytical curves to describe ball drag force. The drag force on both of the balls is less than expected and lower k-factors should be applied. For this case: k=0.25 for a plain ball and 0.45 for the turbine ball. Further the drag force appears to depend on wind velocity with a higher ratio than expected.

10.1.5 Conclusions

Wind load on turbine-shaped ball appears very promising compared to a plain ball, although wind-generated torque remains negligible. Definitely ball shape and surface

structure deserve more close study in order to maximize wind resistance of Thistle-type wind-driven planetary rover.

Drag force as well as dependency on wind velocity differs from the expected. Further tests are needed to qualify the mathematical model and to give realibility for the calculations and conclusions to be made.

10.2 Solar energy

10.2.1 Solar panels

Currently on Mars surface, the Opportinity and Spirit rover solar arrays –when fully illuminated- generate about 140 watts of power for up to four hours per sol (a Martian day) [RD 8]. The solar panels deploy to form a total area of 1.3 square meters (14 square feet) of three-layer photovoltaic cells. The array can produce nearly 900 watt-hours of energy per Martian day, or sol. However, by the end of the 90-sol mission, the energy generating capability is reduced to about 600 watt-hours per sol because of accumulating dust and the change in season. [RD 24]

For a moderate scaled 50 W roving system a 0.5 square meters panel area would be sufficient. However, as mentioned above, lifetime of the solar panels is limited due to dust accumulating onto panel surfaces, if no device for dust removal is implemented. After 180 days the power availability is reduced by almost half. [RD 2] The figure below presents a reduction factor as a function of time of presence on the surface. The first curve, based on Sojourner data, gives a reduction rate of 0.3% for the first 30 days and a slower rate of 0.1% in the following days. The second one, more conservative is based on a constant reduction rate of 0.3%. [RD 2]

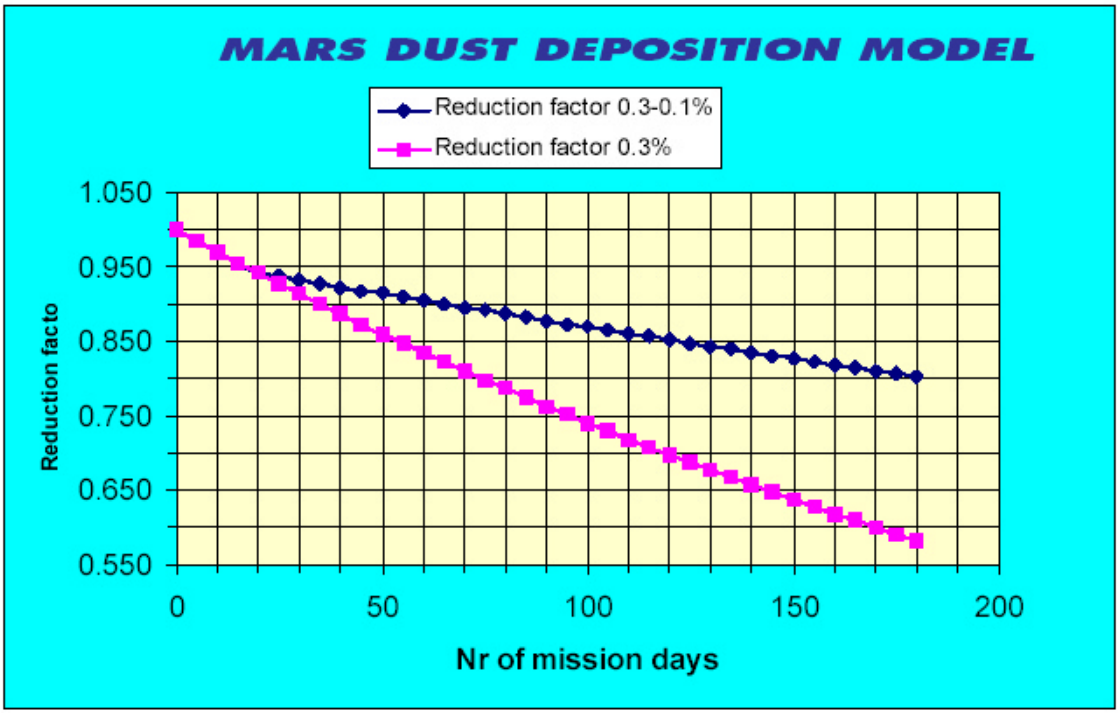


Figure 45, Solar panel efficiency reduction due to dust deposition. [RD 2]

The solar panels also require proper alignment with respect to sun direction to operate properly. Hence a steady platform, like a big-wheeled rover, is needed to carry them. Availability of solar energy is also dependent on the season of the year.

In context of biologically inspired locomotion and energy concepts solar cells can be considered as a trivial solution, and will be studied more accurately only if their utilization turns out to be a preferred solution.

10.2.2 Other methods using solar light

Abundance of carbon dioxide and solar radiation opens an interesting possibility to utilize biological photosynthesis for energy production. In practice photosynthesis turns solar energy into chemical energy that must be converted further into electricity or other forms of energy to be utilized. Fuel cell technology could be a method to produce electricity. Photosynthesis, however, relies on activity of living life forms, and sustaining life on Martian environment is a challenge alone.

10.3 Heat

Heat on Martian surface is one form of solar energy. Heat is produced by absorption of solar radiation. Collecting heat-energy is in principle quite easy; with a properly designed surface properties absorption can be maximized and reflection/emission minimized. In

practice heat energy can be collected with passive components, while active components (like heat pipes) can be used to transfer energy. Also storing of heat is possible with passive means; a simple well-insulated mass can be used. Active systems, based on phase transformation –as for an example- can be used for a more efficient energy storage. As like solar cells, also heat-absorbing surfaces may suffer from dust deposition or other changes on surface properties. However, this effect can be expected to be of less importance. Dust deposition and surface ageing can be expected to reduce reflective properties of bright surfaces, which is only beneficial for heat collecting surfaces.

In general utilization of heat energy relies on temperature difference, not on absolute temperature alone. Thermal engines -like Stirling engine-, peltier elements, and smart materials -like bi-metals and shape memory alloys-, all generate mechanical or electrical energy from temperature difference. Temperature difference may exist either in time (sequential heating and cooling) or in place (other end in hot and other end in cold).

Diurnal variation in Martian air and soil surface temperature is 80-100 degrees in hot case, as presented earlier. Similar changes in rover surface temperature can be expected with a proper design. This temperature variation can be utilized to produce energy on a daily cycle. In cold case and in winter time the variation is much less.

Localized temperature difference can be found between air and ground. However, the difference changes during the day so, that in the morning the ground is colder than air, while in the evening ground is hotter than air. Localized temperature difference can be also found over different parts of the rover. Sunny side of the rover might be hotter than the side in shadow, or exterior parts can be hotter/colder than the interior parts. A rotating wheel transfers its surface continuously from sunny side to the shadowed side.

A hot surface would be constructed of VD-gold hot thermal blanket (absorption factor 0.28 and emissivity 0.02). In stationary state absorbed energy equals to emitted energy:

$$se \cdot \left(T^4 - T_2^4\right) = aB$$

$$where:$$

$$s = 5.67 \cdot 10^{-8} \frac{W}{m^2 K^4},$$

$$T = object\_temperature$$

$$T_2 = environment\_temperature$$

$$B = Energy\_flow\_onto\_surface$$

If emitting area is double of the absorbing area (like a sheet that is illuminated from one side), the left side of the formula can be multiplied by two. For given emission and absorption factors, assumed 320 W/m2 sun radiation (example peak 480 W/m2 [RD 2])

and –140 °C (133 K) sky temperature we get T = 446 K (174 °C). This applies for vacuum. In Martian atmosphere transmission losses and convection decreases the stationary state surface temperature.

Upper limit on thermal efficiency is set by the Carnot law µ=? T/Tcold. The table below shows some values for Carnot-efficiency on possible Martian temperatures. With moderate temperature difference at Martian average air temperature a 15 % Carnot efficiency can be calculated. If we assume 0.28 absorption factor for Sun energy (320 W/m2) and Carnot efficiency 15%, energy to be collected remains 0.28 * 320 * 0.15 or 13 W/m2. Real efficiency depends on properties of energy collection system.

Carnot-efficiency (Martian hot season.)				
Tc (°C)	**Th (°C)**	**DT**	**eff**	**Note**
-130	**-40**	90	**39%**	Tc = sky temp.
	0	130	**48%**	
	20	150	**51%**	
	50	180	**56%**	
	100	230	**62%**	
-80	**-40**	40	**17%**	Tc = low air temp.
	0	80	**29%**	
	20	100	**34%**	
	50	130	**40%**	
	100	180	**48%**	
-40	**-40**	0	**0%**	Tc = average air temp.
	0	40	**15%**	
	20	60	**20%**	
	50	90	**28%**	
	100	140	**38%**	
Tc = Cold temp. Th = Hot temp. DT = Temp. difference, eff. = Carnot efficiency				

Table 12, Example values for Carnot-efficiency on Martian temperatures.

If on purpose generating thermal gradients over mechanical structures of the roving system, one needs to make sure that thermal gradients and thermal variation do not endanger operation and durability of the system.

In the following sections some methods to utilize thermal energy are discussed.

10.3.1 Peltier elements

For many space exploration missions the light from the sun is too weak to power a spacecraft with solar panels. Instead, the electrical power is provided by converting the heat from a heat source into electricity using thermoelectric couples. Such Radioisotope Thermoelectric Generators (RTG) have been used by NASA in a variety of missions such

as Apollo, Pioneer, Viking, Voyager, Galileo and Cassini. With no moving parts, the power sources for Voyager are still operating, allowing the spacecraft to return science data after over 25 years of operation. [RD 27]

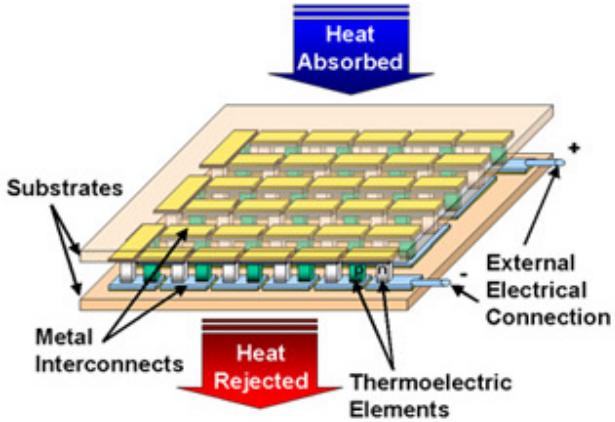


Figure 46, Thermoelectric Module (JPL) [RD 27]

A thermoelectric converter consists of several n- and p- type semiconductor thermoelements, which are connected electrically in series and sandwiched between two electrically insulating but thermally conducting ceramic plates to form a module. Upon a temperature difference across the module electrical power will be delivered to an external load and the device will operate as a generator. Conversely, when an electric current is passed through the module, heat is absorbed at one face of the module and rejected at the other face; thus, the device operates as a cooling element.

The JPL Thermoelectrics Website [RD 27] presents a new branch of miniature thermoelectric modules based on MEMS-technology. Thermoelectric microdevices can convert rejected or waste heat into usable electric power, at moderate (200-500K) temperatures and often with small temperature differentials.

Miniature Radioisotope Thermoelectric Power Cubes, developed at JPL [RD 28] would be heated with 4.2 W radioactive-decay energy up to 200 °C. A 0.2 cm3 cube would have dimensions 0.58 x 0.58 x 0.58 cm, or 6 faces 0.34 cm2 each totalling 2.05 cm2. Each face holds 50 thermocouples and the 300 thermocouples together generate 240 mW of power (12 Volts, 20 mA). Overall thermal-to-electrical energy-conversion efficiency is between 5 and 6 percent. (5% of 320 W/m2 Sun flux on Mars would be 16 W/m2.)

Assuming a 5% efficiency for a pelter element on Thistle surface, approximately 1 m2 for each subsystem (Locomotion, Navigation, Household, Communication, Instruments) would be needed. Efficient area being heated by the Sun would be less than a hemisphre; assume 1/4 of the ball surface being efficiently heated (45 degrees angle of view, allows 29 % reduction in heat radiation intensity). For a 1.5 m sphere this would make 1.8 m2,

for a 3 m sphere 7 m2 and for a 6 m sphere 28 m2. Obviously a 3-m Thistle would have sufficient surface area to carry enough Peltier-elements for Thistle power generation –if utilizing power density familiar from JPL miniature power cubes.

Since the Thistle moves by rolling, the Peltier elements must be placed all over the ball surface. It needs to be studied how much weight such a Peltier-blanket would have. The MEMS-Elements can provide a mass-effective solution. Another topic to consider is availability of required temperature difference. The ball surface can become very hot under Sun radiation, but where we can find the cold side? The commercial Peltier elements require the hot side on the other side of the element, and cold on the other. This would mean that interior of the ball should be cold and exterior hot. It can be a challenging task to maintain interior cold temperature under continuous Sun heating.

10.3.2 Fluid circulation

In nature thermal circulation of fluids is a common phenomenom. Winds originate from heating of air on certain parts of Earth, hot smoke raises upwards from the candle, hot water rises above cold water, a hot-air-balloon floats carried by colder air. Energy of fluid flow can be transformed into electrical energy with turbines and generators. Also a mechanical motion can be generated from fluid flow; if considering a wheel or a ball –as for an example, fluid flowing from one part to other part moves mass and so changes location of mass center. This may cause an unbalance which in turn makes the system rotate to restore the balanced position.

In the following sections utilization of fluid flow is discussed, as a means to provide electricity and as a means to generate direct mechanical by unbalancing a wheel or a ball. Then some methods to generate desired fluid flow are discussed.

10.3.2.1 Radial flow

In the radial-flow concept heat makes the fluid -gas or liquid- flow from outer surface of the wheel or ball towards interior parts. As the heating energy comes from the sun, only half of the ball is illuminated and heated. From these parts the fluid flows towards inner parts. Energy can be collected from a gas flow by using turbines and generators; mechanical motion develops when mass of liquid moves from outer surface closer to the ball center. Resulting unbalance makes the ball to rotate and expose new surface area for sun heating.

10.3.2.2 Tangential flow

In the tangential-flow concept the ball –or a wheel- is divided into several tangential sections. Sun radiation heats up a limited number of sections while the rest remain in cold state. Resulting temperature difference generates a fluid flow that in turn can be transformed into electrical energy or mechanical motion in a similar manner as above.

10.3.2.3 Heat induced gas flow

Utilization of Martian atmosphere –mainly carbon dioxide- as an active element of the power system is an interesting option since this gas is available all the time. In case some gas should be lost during operation, new can be always pumped from atmosphere.

Heat induced gas pump would operate in a following manner:
The ball surface is divided into several gas containers. Each container extends radially through a valve into internal parts of the ball. The valve is also equipped with a microturbine and generator. In initial condition the ball is in uniform temperature and gas pressure is even in all parts of the gas container. As sun radiation starts to heat the ball surface, the gas also heats up and pressure develops in the outer container. When pressure is high enough the valve is opened and gas flows through the microturbine into inner container of lower pressure. Gas flow continues until pressure difference is zero, and energy is collected with a generator connected to the microturbine. Before evening the valve is closed and high pressure remains in all parts of gas container. During night ball surface cools down faster than internal parts of the ball, and pressure in outer gas container drops. The valve is opened and gas flows through the turbine back to the outer gas container.

The sequence can take place on a daily basis when the ball is parked, and more frequently when the ball is rotating, provided that the heating and cooling speed is high enough compared to ball rotation speed.

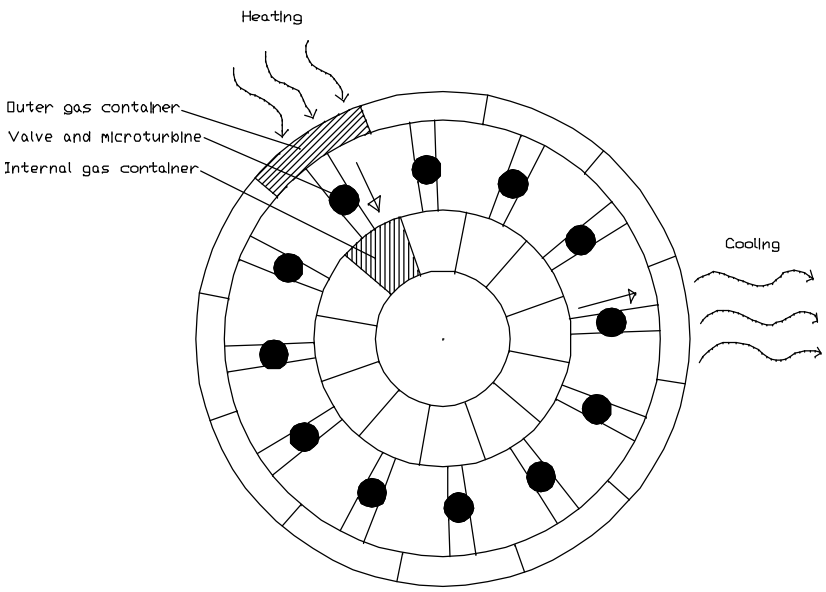


Figure 47, Heat induced radial flow of gas.

An alternative and a simpler method would utilize complete ball volume as a gas container. However, this concept cannot utilize rotation of ball, but relies solely on diurnal temperature variation; during the day the gas inside the ball is heated and pressure develops. In the evening the pressure is released through a microturbine. When pressure difference has disappeared a valve is closed. During the night gas cools down and underpressure develops. In the morning the valve is opened and pressure difference is released through a microturbine.

Energy available for this kind of system can be estimated by calculating energy content of the gas flowing through the microturbine. First we calculate the pressure increase in a closed container as it is being heated by sun radiation:

$$p_1 = p_0 \cdot \frac{T_1}{T_0}$$

Volume of the hot gas, when released to outer pressure is:

$$v_2 = v_0 \cdot \frac{(p_1 - p_0)}{p_0}$$

Where v0 is volume of gas container.
As gas flows from higher pressure p1 to lower pressure p2 and expands simultaneously to volume v2, it has an energy content Wex as follows:

$$Wex = p_2 v_2 \cdot \ln \frac{p_1}{p_2}$$

As the gas expands, it performs work against external pressure p2:

$$W2 = p_2 v_2 \cdot \left(1 - \frac{p_2}{p_1}\right)$$

Maximum energy to be collected from gas is in theory Wex-W2.

Doing the following assumptions:

Container volume	113 m3	Volume of a 6 m ball
Initial pressure	700 Pa	Mars atmosphere
Initial temperature	223 K	Cold air temperature
Hot temperature	293 K	Hot surface temperature

We can calculate the energy available from gas flow. Most of the energy is lost in expansion of gas, and amount to be collected is 847 J. In order to calculate energy content of in-flowing gas as the ball cools down, the initial values can be changed and another energy to be collected becomes 491 J.

Total amount of energy to be collected during one complete cycle is 1338 J. If we assume 20% gain of turbine and generator in transformation to electric energy and 48% efficiency of motor and gearbox, available mechanical energy becomes 128 J or 2 W-min per cycle.

Amount of energy collected is very low. Reasons for low energy gain lie in small heat-induced pressure difference and low gas pressure. If we choose the first option and use a pressurized system we can increase energy gain significantly. If we assume that the pressurized system functions as described in formulas above, we can make new calculations with added pressure. Assumption can be realized with very large or flexible containers, or cylinders which provide a variable volume. The latter case would represent a type of a Stirling heat engine. Assuming 1 bar operation pressure we can recalculate the energy to be collected and we get 18350 J or 306 W-min. This is, a 1-Watt motor can run with this energy for 5 hours, or a 20-W communication system can operate 15 minutes. For 2 bars pressure the result is double.

Drawback with pressurized system is, that high pressure and large variation can cause gas leaks, which must be compensated by pumping new gas in. This would decrease system efficiency. Also gas flow and gas expansion must take place in closed volumes which causes higher resistance for gas expansion and smaller energy gain. Variable volumes realized with cylinders and pistons can give a solution, but with added mechanical complexity and mass. However, replacing the turbine with a Stirling-engine it can be possible to increase total efficiency in transforming the heat energy into mechanical motion.

10.3.2.4 Micro turbines

The MIT Micro Gas Turbine Engine Project has the goal of using MEMS fabrication technologies to construct compact electric power generation systems from a gas turbine generator comprising a compressor, combustor, turbine and electric generator. Another system under development is a stand-alone turbine/generator. Detailed models of the electric induction machine have been developed and used to design an optimized 6- phase machine having a 4-mm diameter. Operated as a generator, this machine is expected to output 0.5 W at 300 V and 1.5 MHz. An initial set of motor/generator devices have been built; see image below. [RD 29]

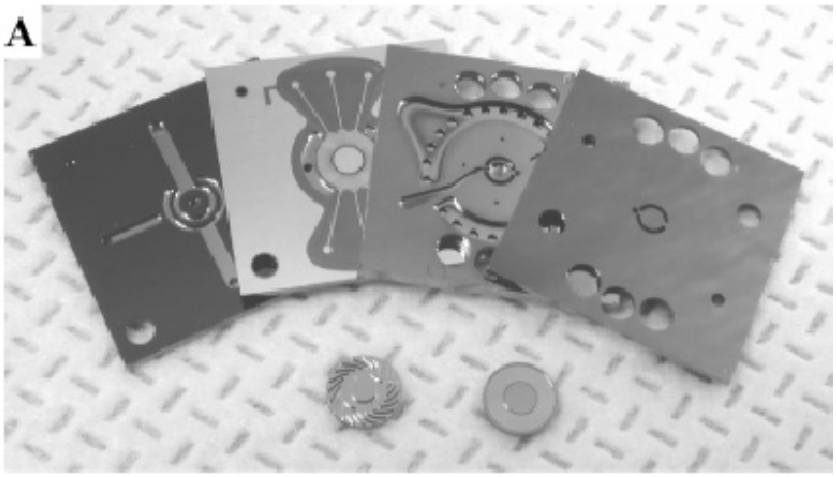


Figure 48, A Micro Gas Turbine (4-mm dia.) developed at MEMS@MIT. [RD 29]

10.3.2.5 Heat induced liquid flow

Transfer of gas does not easily generate significant off-balance due to low mass of gas. On the contrary, transfer of liquid would move much higher mass. However, thermal expansion of liquid is much less than that of a gas. A solution could be phase transformation of liquid into gas upon heating. Operation of liquid/gas torque wheel would be like the following:

Fluid containers would be constructed in a tangential series around the ball or wheel. The containers are separated from each other with a valve, so that fluid can circulate only in one direction. When cold the fluid remains in liquid state. Upon heating the liquid vaporizes and expands. Expansion generates a pressure that pushes liquid in other containers in the direction stated by the valves. The section being heated remains with less mass, while some mass in liquid form moves to opposite side. Resulting off-balance makes the wheel to rotate and exposes new sections for sun heating. Already heated part rotates into shadow and starts cooling and changes state back to liquid.

The tangential container system must have some structural flexibility to allow circulation and uneven accumulation of the liquid, since the liquid is non-compressive by nature. The valves are equipped with socks that allow expansion of gas, but prevent gas from flowing from one compartment to another. If the gas would be able to flow freely, it would find its way to uppermost part of the wheel, and would not generate any off-balance to rotate the wheel. The wheel tends to rotate away from the sun. As the sun moves from one side of the wheel to the other side, the wheel changes its direction of travel. Therefore there exists a moment, when the wheel does not move, provided the sun passes straight above the wheel.

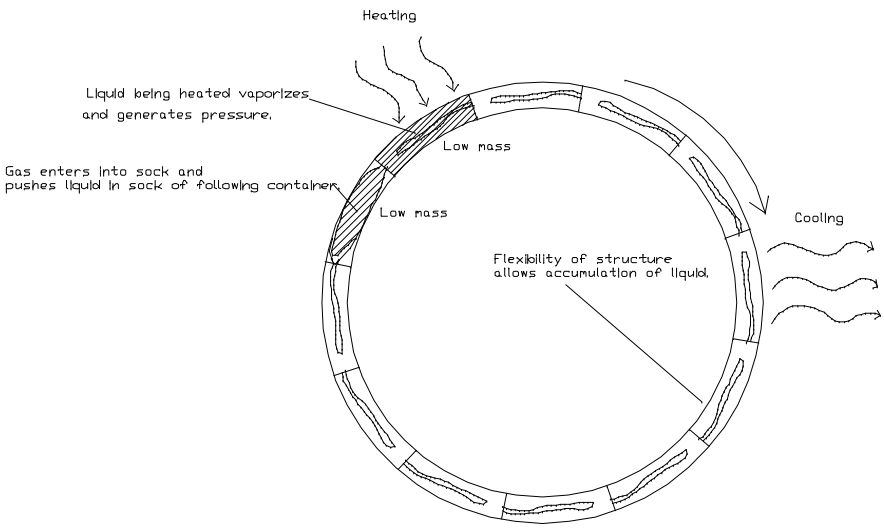


Figure 49, Heat induced vaporization and tangential flow of liquid.

10.3.2.6 Osmosis

Another biological method to generate fluid circulation is osmosis or diffusion. Here fluid flows autonomously through a semi-permeable membrane, driven by different concentration of fluids on both sides of the membrane. The concentration difference tends to approach zero. Large trees elevate water from roots to the uppermost leaves with this method. In order to utilize external energy source (heat) we need to find a way to control this diffusion flow with external heat. One option could be to develop such a fluid that would change its concentration upon heating/cooling. The fluid could be an over-saturated solution that contains excess component in crystallized form. Upon heating the fluid can dissolve more of this component and it's concentration increases, which causes fluid to flow through a membrane.

Operation of the wheel/ball would be similar to one illustrated above. Fluid containers would be constructed in a tangential series around the ball or wheel. Tangential flow of fluid would cause an off-balance on the wheel and would make the wheel to rotate. Rotation of the wheel would expose a new fluid container for heating and the process repeats. The tangential container system must have some structural flexibility to allow circulation and uneven accumulation of the liquid, since the liquid is non-compressive by nature.

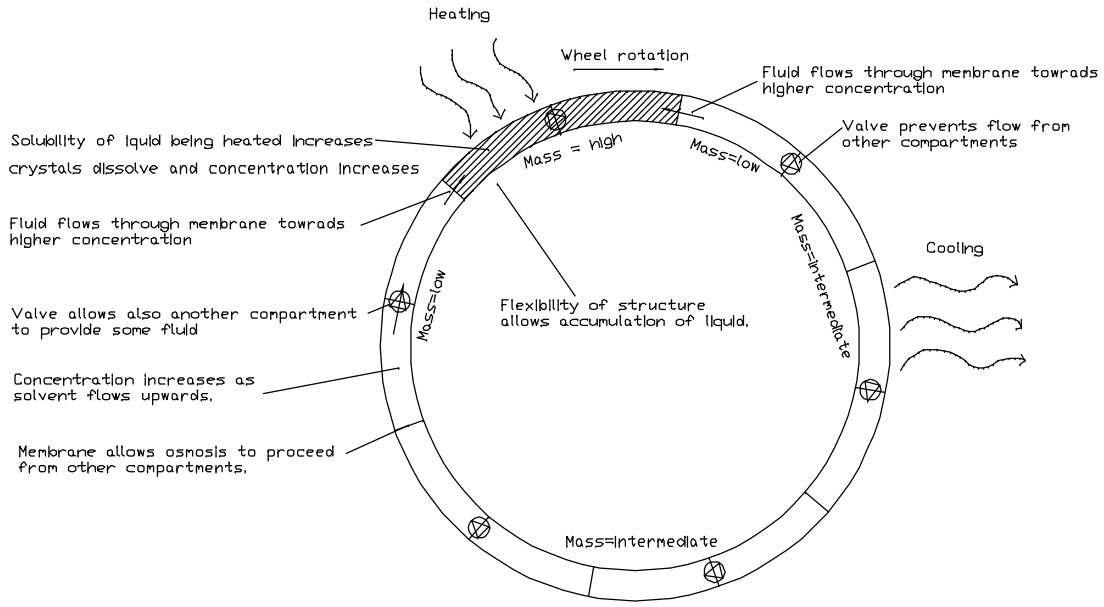


Figure 50, Heat induced osmosis driven fluid flow.

Considering the concept of tangential flow and vaporization, the sketch shows a design where vapor generated in one container flows into two containers, and fluid of one container is divided by the rest 10 containers. Hence the two containers will have a total mass of one container, and the 10 containers will have a total mass of 11 containers. If we assume that ball diameter is 6 meters, tangential length of container is 30 degrees i.e. 1.57 m and effective width of containers (area to be heated) is 90 degrees i.e. 4.71 m. Assume container thickness 0.01 m. Volume of one container is then approximately 0.074 m3 or 74 litres. Total volume is 12-fold i.e. 0.887 m3 or 887 litres.

Assuming (just for an example) that the containers are filled with water (total mass of 887 kg!), one container would weight 74 kg. Resulting off-balance would depend on the angular position of the area being heated. Maximum radius of moment would be 3 m and minimum radius 0 m. Off-balancing force would equal to weight of one container that has been removed by vaporized gas. Thus maximum off-balance torque would be 74 kg x 3 m x 3.7 kgm/s2 = 821 Nm. Practical off-balance could be roughly 1/3-rd of this i.e. 273 Nm.

Resulting off-balance seems attractive, but a severe penalty is the total mass of the system. Utilizing a smaller amount of liquid or liquid with smaller weight would reduce the total mass, but also the torque would be reduced respectively. It is possible to make larger containers and use total of 8 instead of 12 containers, but still the resulting torque with respect to total mass would not reach a favorable ratio. A concept to collect all of the liquid into one location could save a lot of mass.

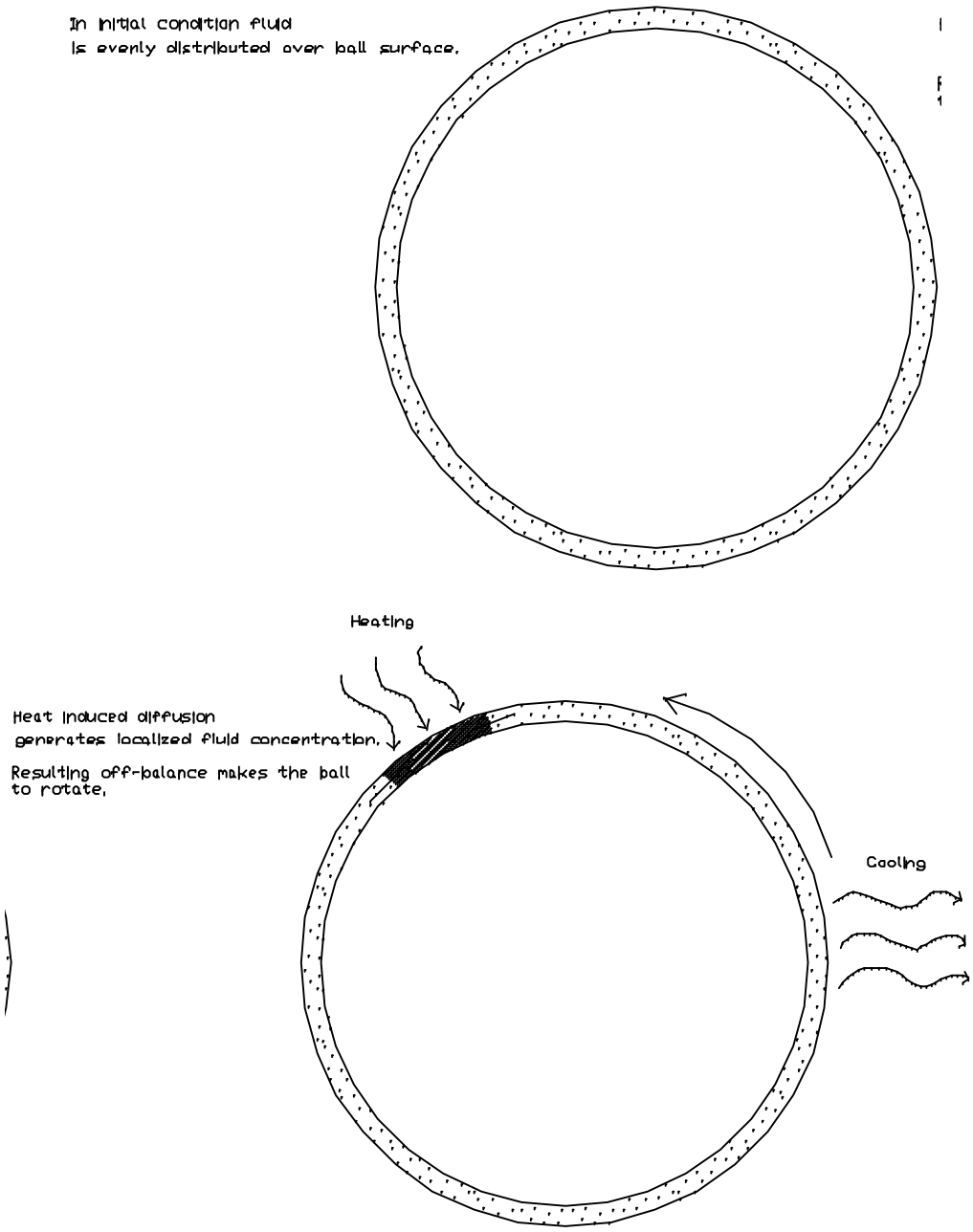


Figure 51, Heat causes fluid concentration in a sponge-like material.

Osmosis or diffusion could perhaps concentrate the fluid on the area being heated, if the wheel/ball surface would be constructed of a sponge-like material, and leave the other parts dry. Another solution could a sort-of shrink-tube, that shrinks in cold and expands when hot. In cold areas of the ball the tube shrinks and pushes the fluid into hot areas, where the tube expands. With these solutions we can produce similar un-balance as above, but keep the ball mass low at the same time. The shrink tube would be preferably constructed of some plastic material with low mass and high coefficient of thermal expansion. A wowen net-like exterior structure can improve diametral changes as temperature varies. Also bi-metals and shape-memory alloys can be used to construct a shrink-tube, but with some added mass.

10.3.2.7 Discussion on fluid circulation

The radial gas flow appears quite straightforward solution. Its only drawback with respect to other two solutions is that it needs additional actuators to generate motion. The two other solutions would provide autonomous rotation without any actuators. However, due to control and navigation needs the actuators may be required anyway.

The tangential liquid-flow that is based on vaporization appears quite challenging when considering handling of vapor and liquid in the same volume. The biologically inspired option to use diffusion, osmosis or dialysis to cause fluid flow provides another operation principle. Also thermally actuated shrink-tubes can be used to concentrate the fluid on the hot areas.

The concepts presented above utilize a tangential mass to generate a locomotion torque. This fluid would be only a ballast mass (several tens of kilograms) and it would be more useful to utilize some active and useful mass that would be carried along in any case. This could include batteries and other structural mass. This option is to be discussed later.

10.3.3 Direct conversion to mechanical motion

Smart materials, like bi-metals and shape memory alloys, react to temperatures or temperature variations by changing their shape. This change can be used to perform some work and propel a rover into motion.

Operation of bi-metals is based on different thermal expansion of two tightly bonded metal strips. The structure bends as the other metal expands/shrinks more than the other. One example is an old-time thermometer or car thermostat. As thermal expansion alone is usually small, the difference between two materials along a long joining seam can produce large variations in curvature and large movements in the end of a beam. Energy can be collected, or work performed, upon heating and/or cooling of the system.

Operation of shape memory alloys is based on change in crystal structure of the alloy. There are several commercial alloys and the Nickel-Titanium is largerly used and possesses good technical properties. Ni-Ti alloy can reproduce (recover) geometrical variations of 5-8% in dimension. Force to be generated depends on amount of material being heated. Recommended recovery stress for Ni-Ti alloy is 170 MPa. It is evident that geometrical variations are small in general, but great forces can be generated. With certain mechanical solutions, like springs, levers or pulleys, geometrical variation can be enlarged but respectively output force is reduced. [RD 25]

There are two types of shape memory effects: one-way and two-way. One-way effect needs to be restored (deformed) after heating into shape it was having before heating. This deforming operation for Ni-Ti alloy requires 70 MPa stress. Two-way effect regains the as-cold geometry autonomously, but available output force becomes low. Recovery temperature of Ni-Ti alloys can be adjusted to any temperature between –60 and +100 centigrade, so it suits well on Martian environment. [RD 25]

Typical for bi-metal or shape-memory actuators is that the resulting motion is limited and a continuous motion must be generated with several sequential and repetitive motions. Then the actuators must heat up and cool down in a sequential manner. In order to maintain reasonable locomotion speed heating and cooling can not be tied to diurnal variations, but it should rely on rover motion or other external motion that would re-direct heating to the desired actuators in a desired manner. Obvious approach would use direct sun light for heating, and cold Martian air for cooling. Utilization of heat stored in Martian surface can be difficult since in the morning it is colder than air, and in the evening it is hotter than air. Also contact to the ground cannot be predicted due to distribution of rocks and boulders.

10.3.3.1 Continuous acting SMA-heat engines

There do exist several solutions to produce continuous motion with SMA-engines. However, currently their efficiency is quite low and their design and operation is quite complicated regarding the distribution of hot and cold energy in Martian conditions. [RD 26]

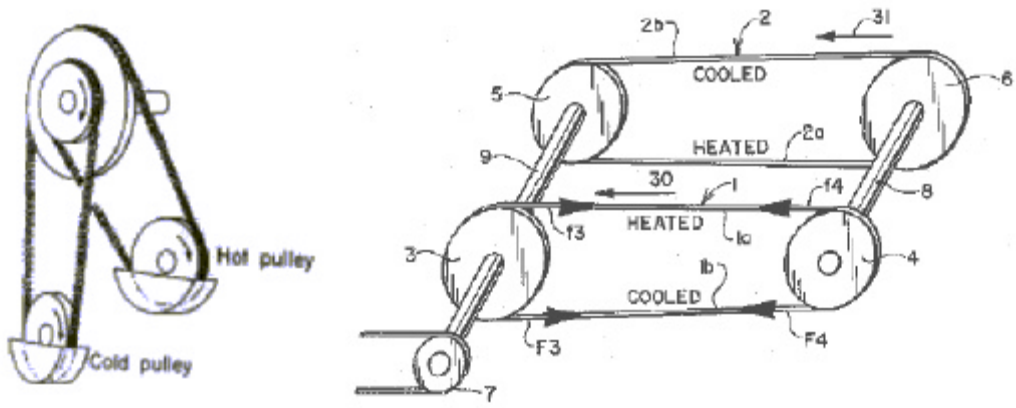


Figure 52, Some early SMA-heat engines. [RD 26]

10.3.3.2 Heat-induced structural deformation

Structural deformation could be used to deform the ball or wheel structure to cause off-balance that would in turn to make the ball/wheel roll. This approach suits only on areas/times where sun shines from a low angle. If the sun should shine from a very high angle, the top part of the ball/wheel would deform, and the resulting off-balance would not cause any motion any more.

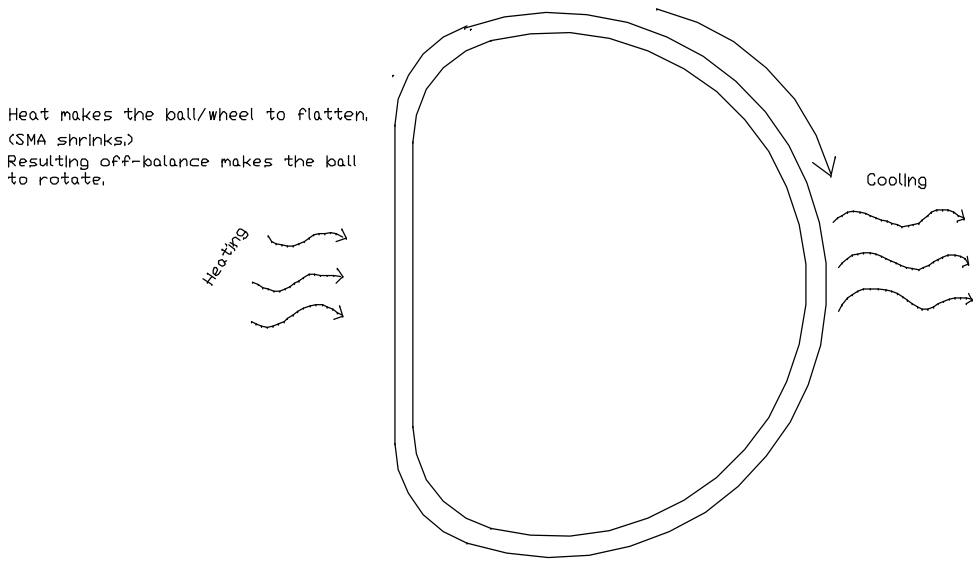


Figure 53, Heat deforms a SMA-constructed ball/wheel surface.

Heat could also cause some protrusion with a ballast to move and so cause un-balance. It would be beneficial to let the protrusion extend inside the ball, so that any external protrusions would not prevent ball rotation, or would not stick to any stones or holes around. A 6-m diameter ball would provide enough volume for this.

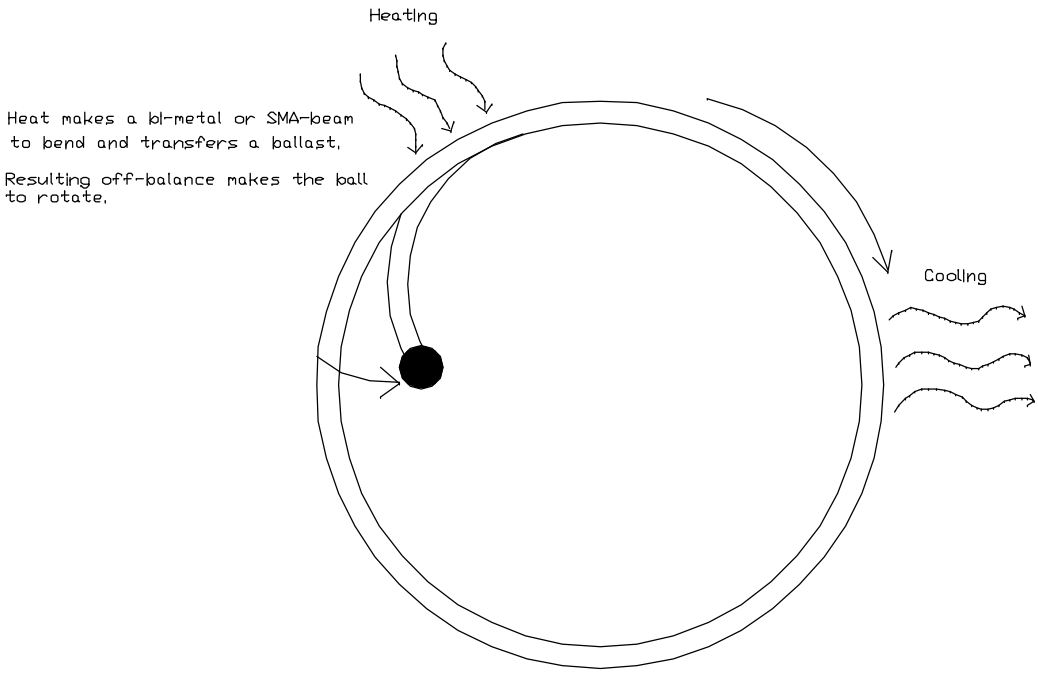


Figure 54, Heat moves a ballast inside the ball/wheel.

Considering the image above, we can assume that the beam holding the ballast has a length of 1 m, and it bends so that the ballast moves radially 200 mm inwards. (Similar performance has been demonstrated with a small-scale model with NiTi wire actuator.) If the ballast has a mass of 2 kg (a battery, as for an example), relocation of the mass causes an unbalance that has a magnitude of mass times radial dislocation, i.e. 2 kg * 0.2 m = 0.4 kgm or 1.5 Nm in Martian gravity. Torque can be increased by adding number of beams and ballast being active. Considering a 18.8 m perimeter of a 6 m ball, possibly 90 active ballasts can be considered –some in parallel-, and the torque can be increased to 130 Nm. The ballast must be present all over the surface, for example18 in line and possibly 15 in parallel, giving total of 270 units. If each weighs 2 kg, total mass of ballast only is then 540 kg.

10.3.3.3 Internal parts as a ballast

The examples above indicate that if using ballast located on ball outer surface to generate rolling torque, overall mass versus torque –ratio becomes poor. The reason is that, as the sphere rotates, the ballast must be available on all parts of the sphere. An exemption is

the concept of collecting small amount of fluid into one single location, leaving all other parts of sphere surface dry.

An alternative solution is to use one single ballast inside the ball and let the ball rotate around it. The ballast would then be carried by and hinged to sphere axis of rotation. The ballast would construct of rover payload: batteries, computers, structural parts etc. So it would not add any dummy mass for the system. If assuming a 40 kg mass for the parts being used as a ballast, a 1 m off-centered distance would generate a 40 kgm or 148 Nm torque on Martian gravity. (1 m off-centering equals to 40 degrees tilt with 1.5 m radius.)

In order to utilize structural mass, batteries, or other active components as a ballast mass external energy should be transferred into internal parts of the wheel/ball, where all the active components are located. There rotation of the components around an axis would generate rolling torque. However, task of conducting heat or heat-induced motion from ball/wheel surface into internal parts is not an easy one. A solution might be to generate electricity on ball/wheel surface (with peltier elements or micro-turbines) and utilize electric motors inside the ball/wheel to generate rolling torque.

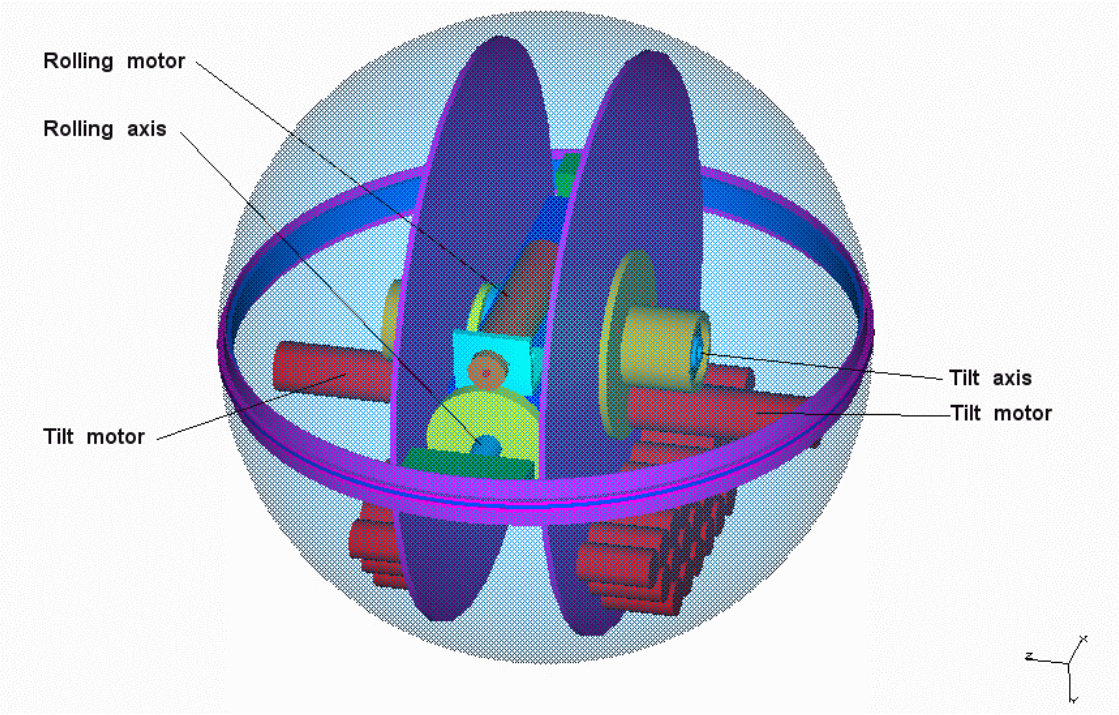


Figure 55, A concept of internal ballast hanging on rolling axis and using electric motors (a 40-cm model).

10.3.4 Discussion on heat as a local power source

Considering the several conceptual methods presented above, the most simple, robust and reliable solutions deserve a closer attention. The heat induced radial gas flow with microturbines provides a mechanically simple and electrically flexible power source.

Using liquids as a moving ballast appears to cause a high mass-penalty and a challenging task to control fluid flow inside ball/wheel structure. In a similar manner also the mechanical concept to transfer ballast from outer surface radially, even though simple and reliable solution, suffers from the fact that the ballast must be present all over the surface. The consequence is that total mass becomes high and ratio between mass and locomotion torque is not sufficient.

A concept that collects all of the fluid into one location at the time could be a suitable solution when considering the resulting off-balanced torque and total mass. A challenge is to find working concepts to collect the fluid into desired location against Martian gravity and thermal variations.

A competing concept using ballast is the internal off-centering of system instrumentation, that can generate high torque with little added mass. A challenge is to utilize external energy sources to relocate internal ballast for locomotion.

10.4 Slopes, wind and re-charging batteries

Slopes do not provide any energy; unless always rolling downwards. However, some potential energy is being collected as the Thistle drives onto a hill. The ballast motors can be used as generators while rolling down the slope, and some of the energy can be restored in the batteries. In a similar manner wind can be used to re-charge the batteries while rolling along with a high-velocity wind.

10.5 Discussion on local power sources

Two locomotion principles have been discussed for the Thistle-rover. It can be either propelled by wind, or it can roll driven by un-balanced ballast. Un-balancing energy source varies largerly. The table below presents utilization of local power sources for Thistle locomotion. Performance of these options is discussed in the following sections after mobility considerations.

Utilization concepts of local energy sources					
Locomotion method	**Power source**	**Power conversion method**	**Power carrying system**	**Used form of energy**	**Locomotion generating system**
Wind propulsion	**Wind**	None (direct)	Martian wind	Wind kinetic energy	None (direct)
Un-balancing ballast	**Wind**	Wind mill	Martian wind	Electricity	Electric motor
	Heat	Micro-turbine	Thermal expansion of gas	Electricity	Electric motor
		Evaporation	Fluid phase transform	Gas pressure	Fluid container as a ballast
		Osmosis	Fluid concentration	Osmosis-pressure	Fluid container as a ballast
		Bi-metal	Thermal expansion of metal	Bending stress of beam	Beam + ballast
		Stirling engine	Thermal expansion of gas	Mechanical motion	Piston + pinion assembly
Ballast or hopping	**Sun radiation**	Solar cells	Solar energy	Electricity	Electric motor
	Heat	Peltier element	Temperature difference	Electricity	Electric motor

Table 56, Utilization concepts of local energy sources

In the table below the energy sources used for production of electricity are compared separately. The 'Notes'-column lists several assumptions that had to be made in order to perform the power and energy calculations. Performance of solar panels is clearly above others, although power from Peltier elements is still sufficient. A wind-mill solution could work if enough wind is present and some time can be reserved to charge batteries. Power gain from thermal expansion of gas inside the ball appears to be very small.

Electricity generation comparison			
Method	**Power**	**Energy**	**Notes**
Solar Panels	271 W (38 W/m2)	130 080 W-min / sol	3-m ball, 25 % surface illumination, 8-hr sun visibility, 12 % efficiency, solar flux 320 W/m2
	1 084 W	520 320 W-min /sol	6-m ball
Peltier elements	113 W (16 W/m2)	54 200 W-min / sol	3-m ball, 25 % surface illumination, 8-hr sun visibility, 5 % efficiency, solar flux 320 W/m2
	452 W	216 800 W-min / sol	6-m ball
Gas turbine + thermal expansion of air in ball	30 mW	2 W-min / sol	700 Pa, 6-m ball, 9.6 % efficiency from gas energy to electricity, assume flow time 1 hr
	5 W	306 W-min / sol	1 bar, 6-m ball
	10 W	612 W-min / sol	2 bar, 6-m ball
Wind-mill	1.08 W	777 W-min / sol	1 m mill, 7 m /s, 40% efficiency, 12 hrs wind / sol
	9.7 W	6 998 W-min / sol	3 m mill, 7 m /s, 40% efficiency, 12 hrs wind / sol
	38.8 W	27 936 W-min / sol	6 m mill, 7 m /s, 40% efficiency, 12 hrs wind / sol

Table 57, Electricity production from local energy sources.

11 Mobility considerations

Before we can compare the performance of different energy sources, we have to consider mobility requirements and also size of the system. Mobility and rolling torque for three different sizes of Russian Thistle –type balls are studied, and needed wind-force or ballast loads are calculated.

As the Thistle hits an obstacle, it adopts a new point of contact. If we wish to overcome the object the needed torque must be calculated according to this new point of contact between the ball and the object. As the contact point moves from ground to the obstacle, also the torque caused by vertical ballast force or horizontal wind-load changes.

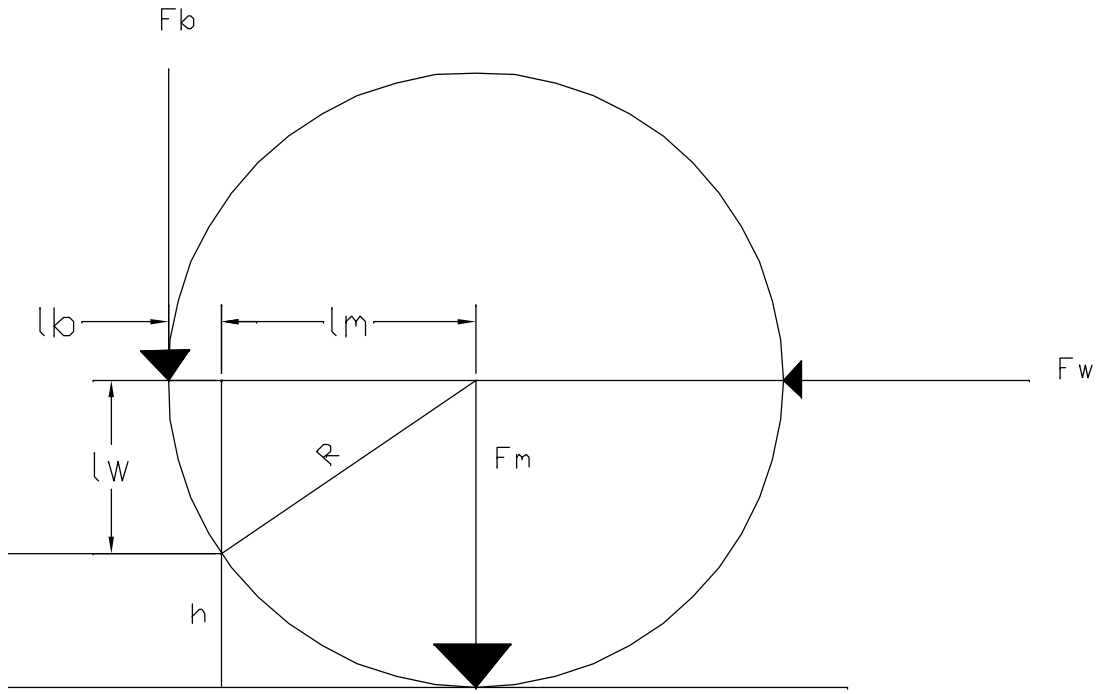


Figure 58, Loads acting on a sphere overcoming an obstacle.

11.1 Wind propulsion

Consider the image above. If the rolling Thistle meets an obstacle of height ‘h’, mass load of the Thistle ‘Fm’ generates a resistive torque with moment arm ‘lm’.

If wind load ‘Fw’ is used for locomotion, the resulting torque with wind-load arm of moment ‘lw’ must overcome the resisting torque. We make an assumption that wind load center goes through the center of the sphere. Reformulating the sphere into wind-turbine can increase the performance some 25% -assuming 10 active turbine blades- and a lighter wind can give a similar locomotion capability.

The results for calculations are illustrated in pictures below. It can be seen that as obstacle size increases, the needed wind velocity increases fast if sphere diameter is small. Even during strong dust storms at 30 m/s wind velocity a small 1.5 m sphere would easily get stuck, a bigger 3 m sphere would have some overcoming capability while a 6 m ball would roll over most of the obstacles. (Note the estimated masses for the spheres with different sizes.)

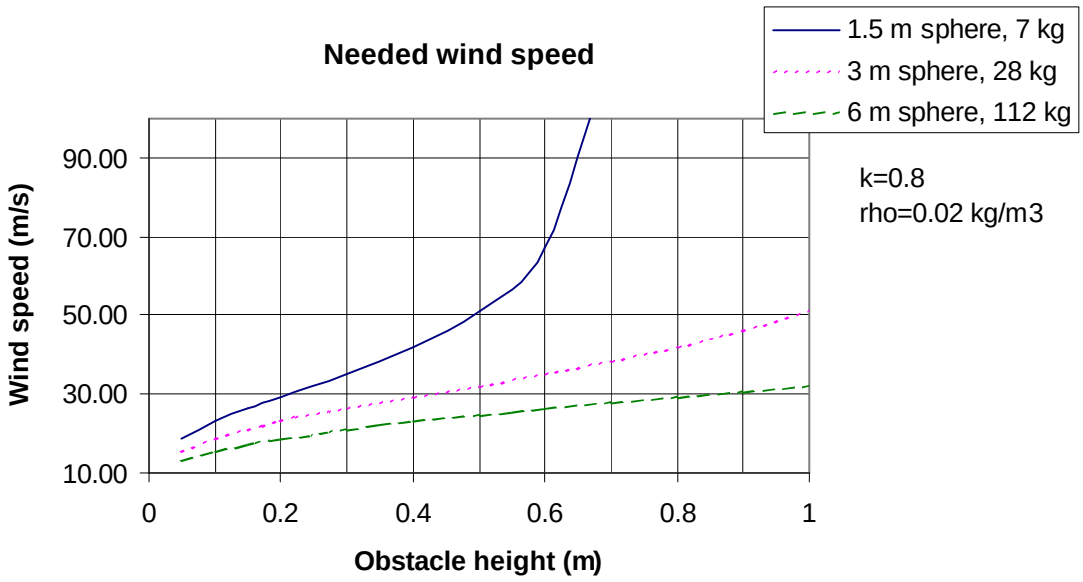


Figure 59, Needed wind velocity to overcome an obstacle.

Performance of the sphere increases if the mass can be kept low. The figure below shows the needed wind velocity for low-mass spheres. Performance of the 1.5 m sphere is still poor. A 3 m sphere would have a good locomotion capability under strong winds, and a 6 m sphere would travel over most of obstacles without difficulty driven only by light winds.

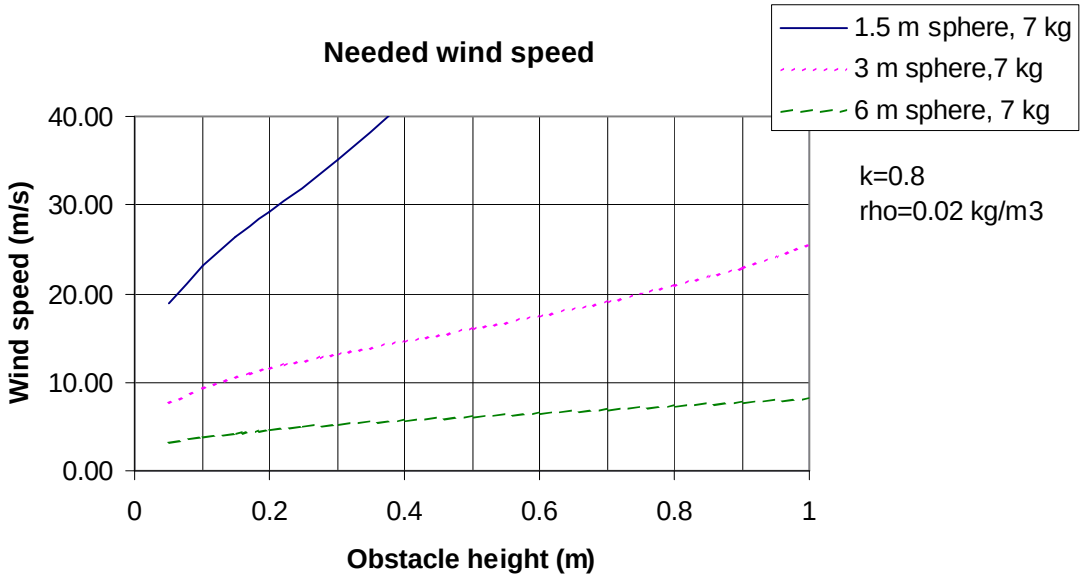


Figure 60, Needed wind speed for a low-mass sphere.

For the interest of the reader the following graphs show how required wind velocity depends on ball mass and obstacle height.

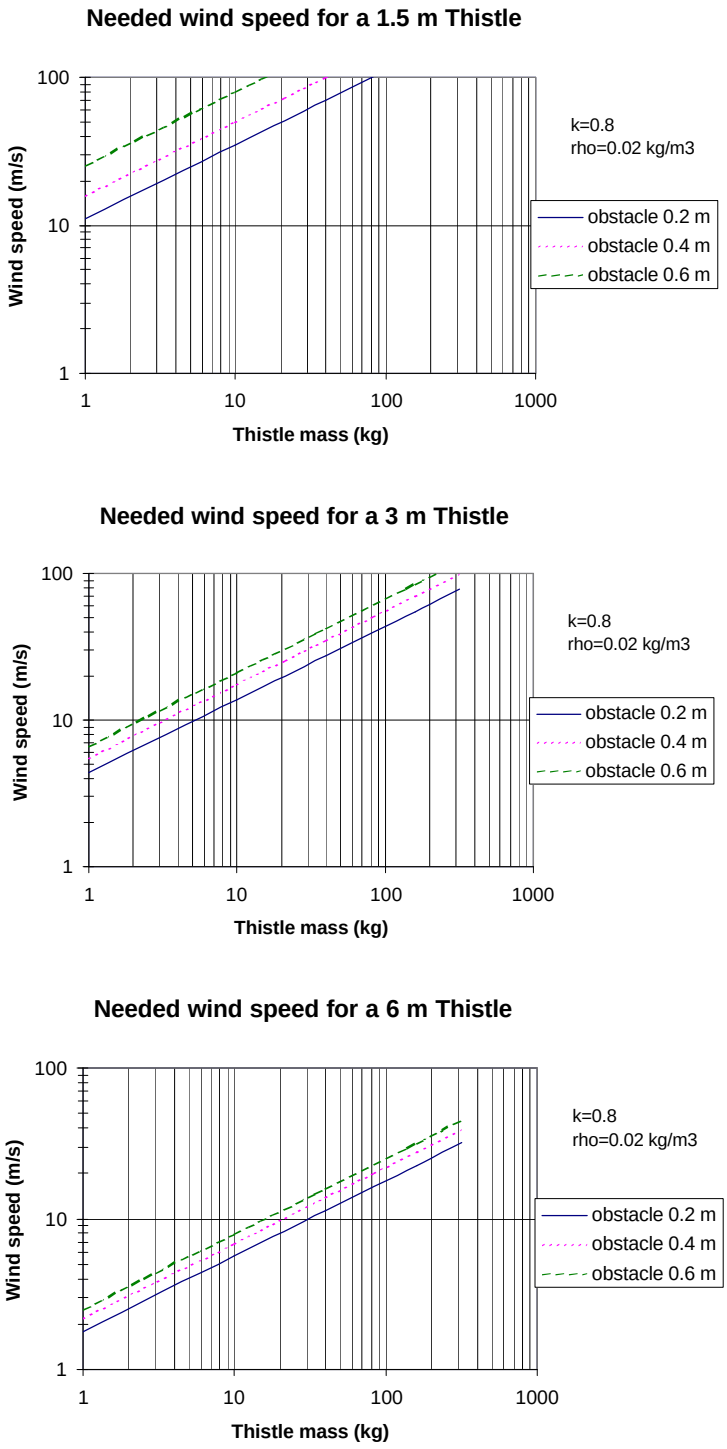


Figure 61, Wind speed requirement as a function of mass.

11.2 Ballast mass

If using un-balanced ballast mass for locomotion the sphere mass must be divided in two portions: an evenly distributed structural mass acting through the center and resulting in resistive torque, and the ballast mass causing 'Fb' and having moment of arm 'lb'. The figure below shows the needed ballast mass to overcome an obstacle. Sphere masses are similar to ones used for wind-velocity calculations. (Note the estimated ball weights.)

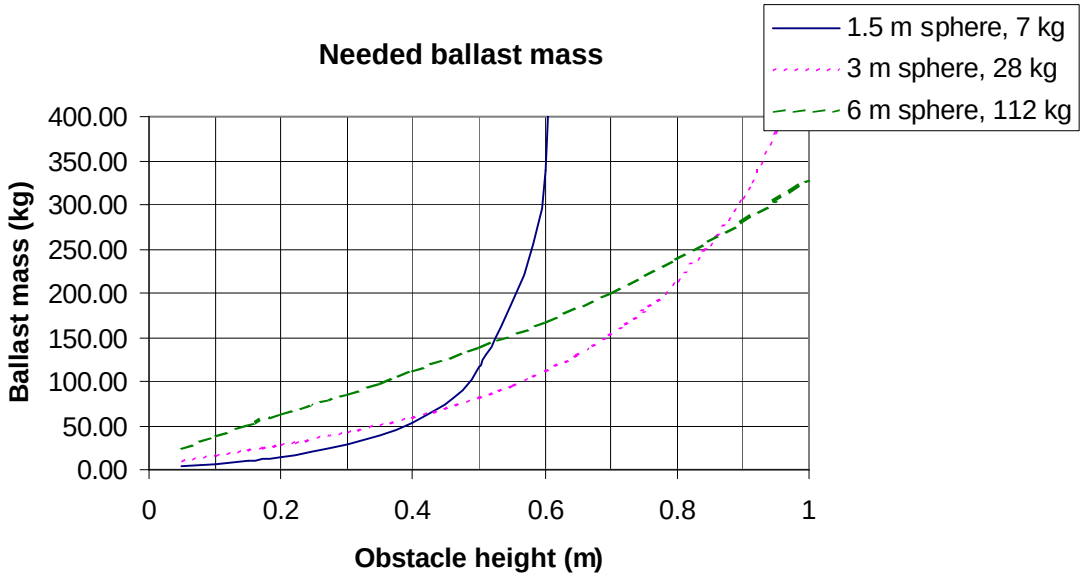


Figure 62, Needed ballast mass to overcome an obstacle.

The figure below shows the performance of ballast mass when the sphere mass is kept low. A good locomotion capability can be achieved with a 50 kg ballast and 7 kg 3 m sphere. An excellent locomotion capability could be achieved with a 20 kg ballast and a 7 kg 6 m sphere.

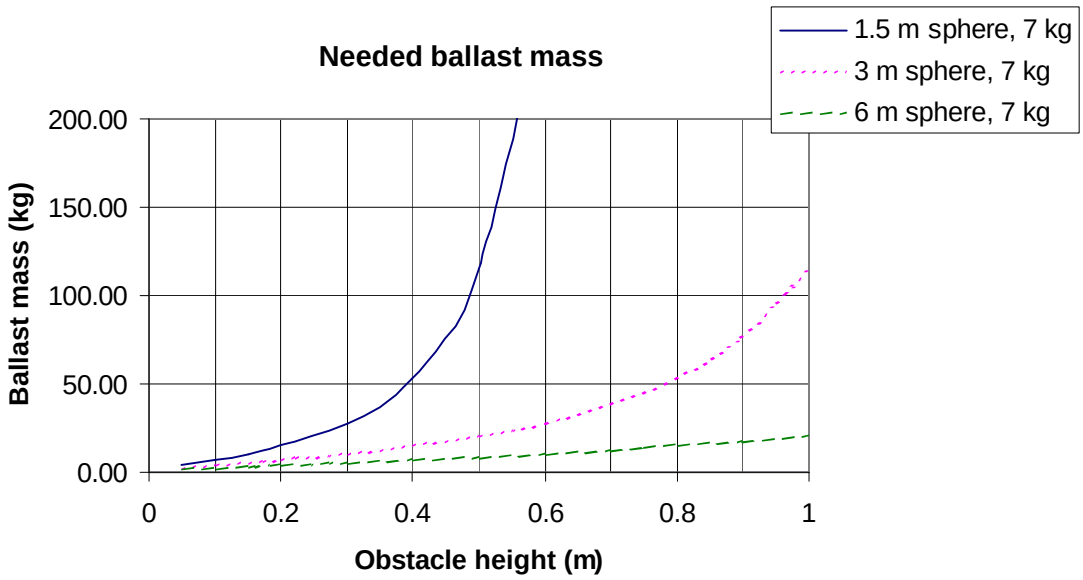


Figure 63, Ballast mass for a low-weight sphere.

For the interest of the reader the following graphs show how required ballast mass depends on ball mass and obstacle height.

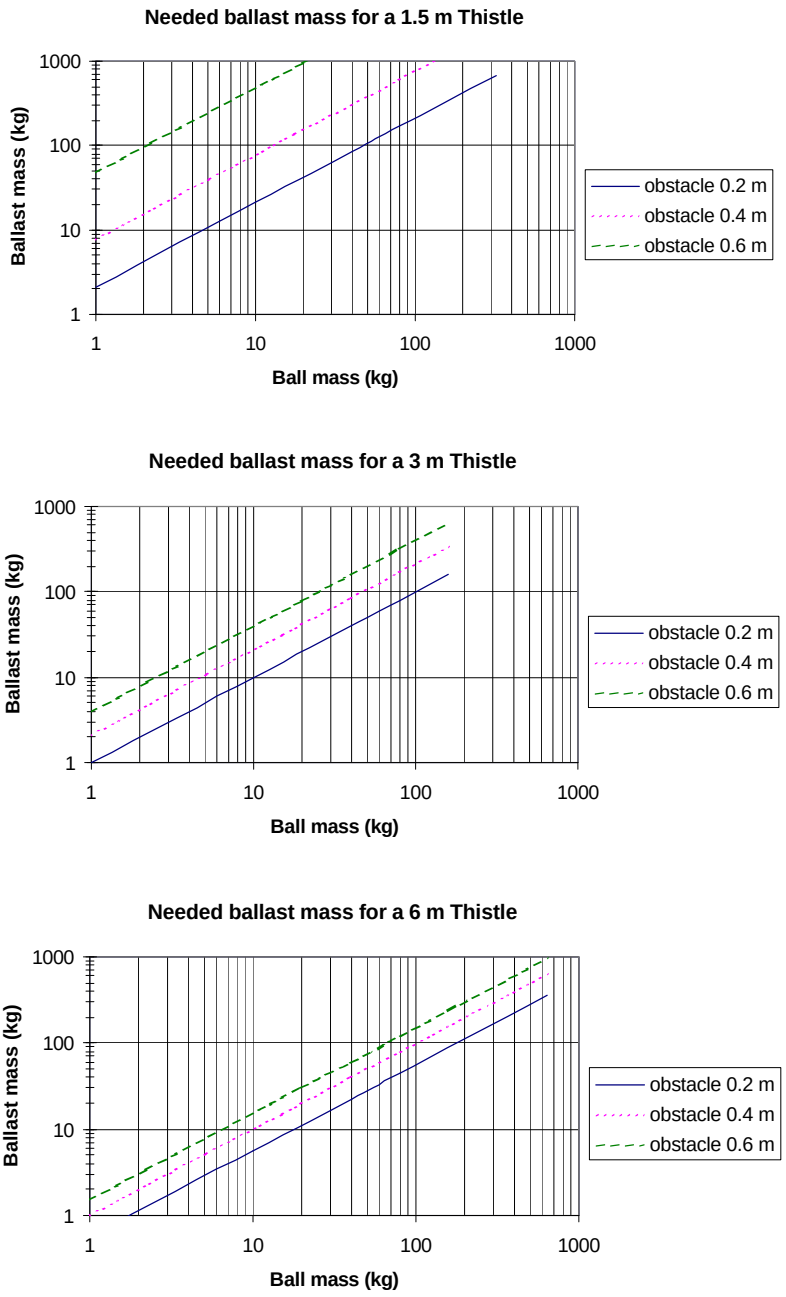


Figure 64, Ballast mass requirement as a function of mass.

11.3 Comparison of wind propulsion and un-balanced ballast mass

In order to compare wind-propulsion and ballast-drive the previously-presented graphs can be collected to one table. The table below presents as a function of Thistle total mass the needed wind velocity or alternatively the allowed sphere mass (the rest of the total mass must be reserved for the ballast) for three different obstacle height.

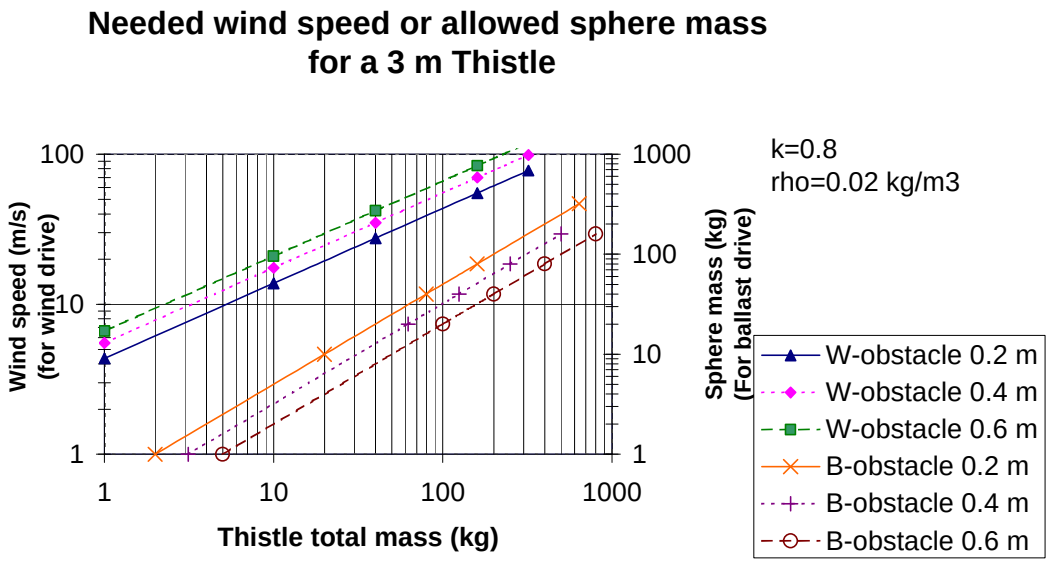


Figure 65, Wind velocity and allowed sphere mass (for ballast-driven concept) as a function of Thistle total mass and obstacle height. (3-m Thistle)

It can be seen from the graph, as illustrated in figure below, that there does exist a range where similar locomotion performance can be achieved with a reasonable wind speed and also with reasonable ballast size/sphere mass. A 3-m Thistle having a 30-40 kg total mass could utilize both methods of locomotion.

On the left side of the graph the total mass becomes so low that mass reserved for the sphere structure becomes very small and ballast-drive can not be realized. On the right side the total mass of the Thistle becomes so high, that unrealistic wind velocity would be needed for locomotion and a ballast drive would provide a better alternative.

If Thistle total mass should fall into indicated overlapping range, either of the locomotion methods would provide a similar locomotion capability. In this case both methods could be implemented for redundancy and versatility.

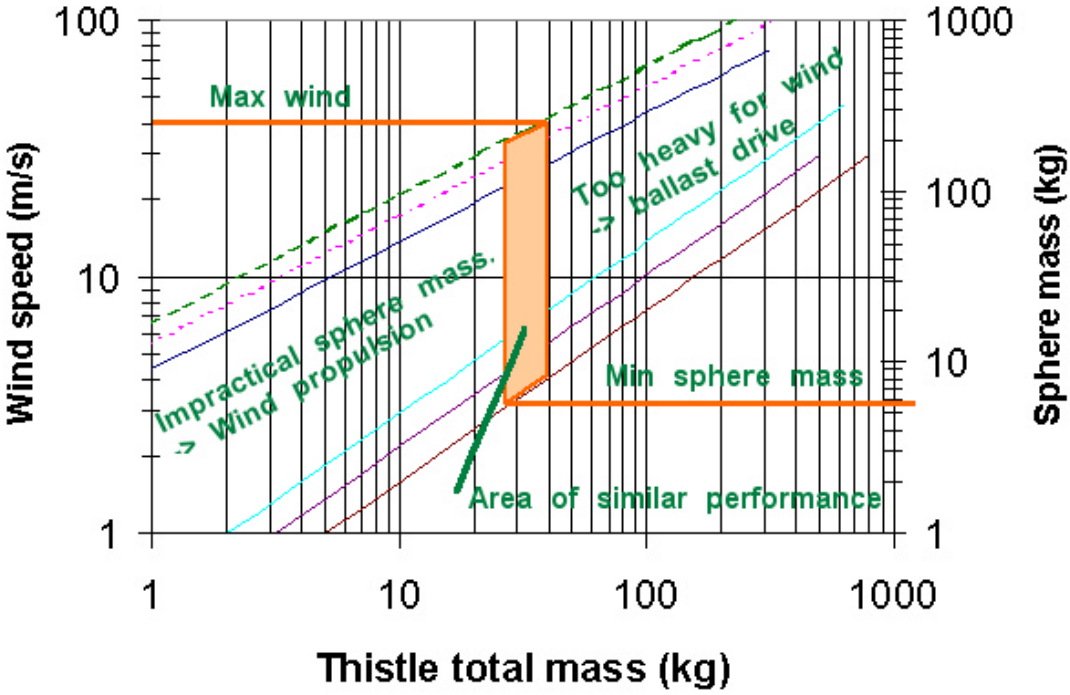


Figure 66, Overlapping region for a similar performance of wind-propulsion and ballast-drive.

A similar comparison as presented above can conducted also for 1.5-m and 6-m Thistles. See figures below.

Wind-propulsion of a 1.5-m sphere is limited to overcome only 0.2-0.4-m obstacles at high wind velocity. Also ballast-drive calls for a Thistle with 20-30-kg mass or more to overcome 40-cm obstacles. There is no overlapping area where both methods could be used for prpulsion.

The 6-m Thistle provides more alternatives. Wind-propulsion is adequate up to 150-kg mass. Total mass of a ballast-driven Thistle starts from 70-100-kg (30-40 kg sphere mass, 40-60 kg ballast) and continues upwards.

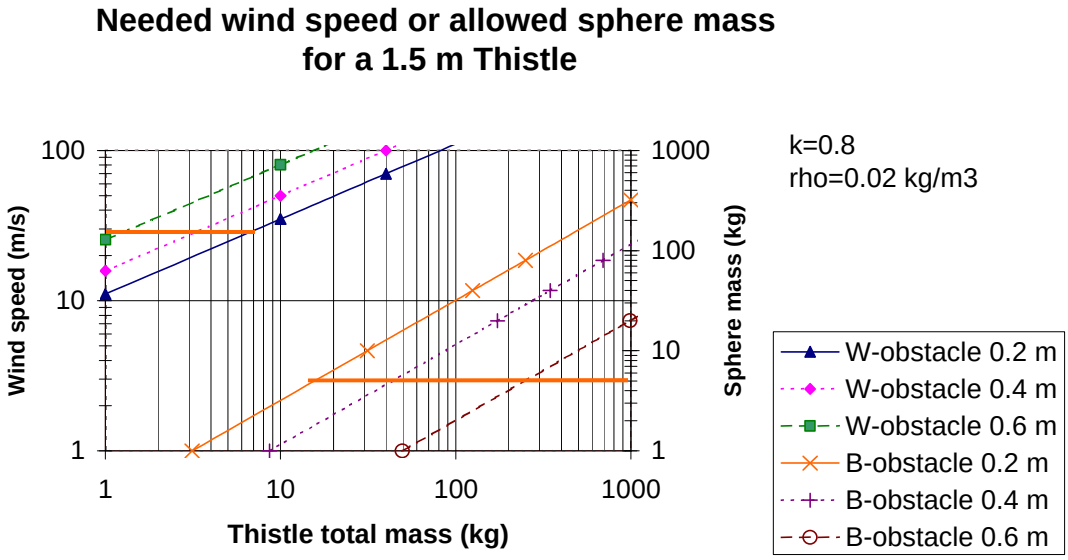


Figure 67, Wind velocity and allowed sphere mass (for ballast-driven concept) as a function of Thistle total mass and obstacle height. (1.5-m Thistle)

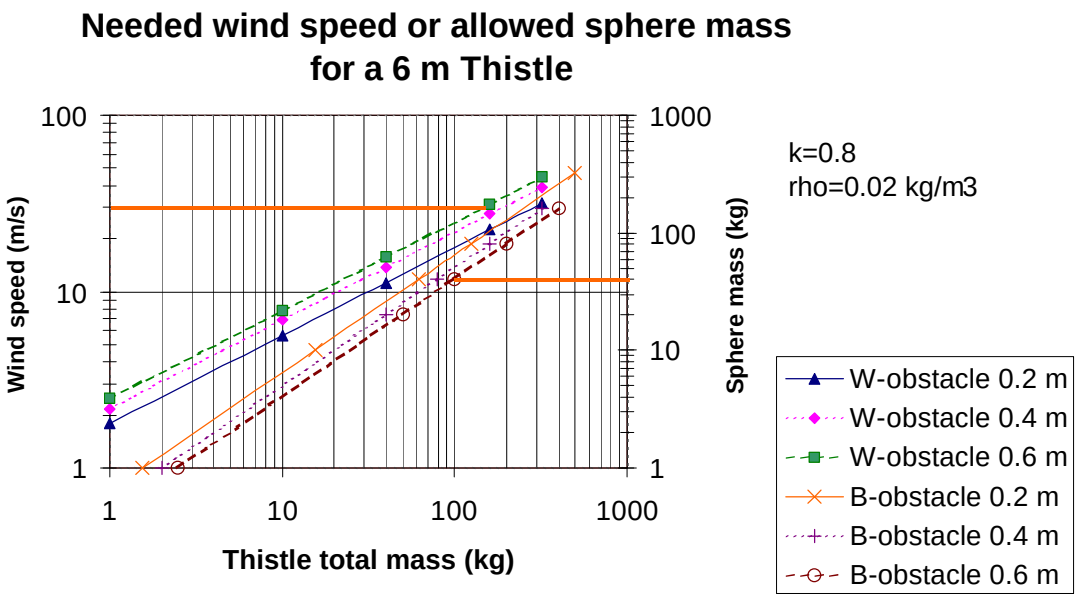


Figure 68, Wind velocity and allowed sphere mass (for ballast-driven concept) as a function of Thistle total mass and obstacle height. (6-m Thistle)

As we have now calculated the basic criteria for the mobility, realized with wind thrust or ballast mass, we can collect the data into the table below and perform a comparison between different concepts. Comparison is not quite straightforward, as performance depends strongly on ball diameter and mass. Therefore some alternative values are presented in order to indicate preferred direction of development.

Comparison of propulsion performance						
Concept	**Ball dia. m**	**Ball mass kg**	**Ballast mass / wind velocity**			**Notes**
			Small obstacle 0.2 m	**Medium obstacle 0.4 m**	**Large obstacle 0.6 m**	
Wind propulsion	1.5	1.5	14 m/s	19 m/s	31 m/s	Very-low-mass solution.
	1.5	4	22 m/s	32 m/s	51 m/s	Low-mass solution.
	3	5	10 m/s	12 m/s	15 m/s	Very-low-mass solution.
Note: Different	3	10	14 m/s	17 m/s	21 m/s	Low-mass solution.
Wind conditions	3	20	19 m/s	25 m/s	30 m/s	Medium-mass solution.
	3	30	24 m/s	30 m/s	36 m/s	High-mass solution.
	6	30	10 m/s	12 m/s	14 m/s	Low-mass solution.
	6	80	16 m/s	20 m/s	22 m/s	Medium-mass solution.
	6	150	22 m/s	27 m/s	30 m/s	High-mass solution.
Wind propulsion with turbine-design	As above	As above	As above 11 % less velocity expected			25 % higher wind resistance expected (k = 1)
~~**Tangential fluid flow; vaporizing or osmosis**~~	~~6 m~~	~~900 kg~~	~~N/A~~	~~N/A~~	~~N/A~~	~~Assumes water density.~~ Total mass out of scope.
~~**Tangential ballast and deformation**~~	~~6 m~~	~~540 kg~~	~~N/A~~	~~N/A~~	~~N/A~~	~~Assumes 200 mm radial displacement of ballast.~~ Total mass out of scope.
Internal ballast; includes also tangential fluid flow; mobile fluid ballast.	1.5	1.5	3 kg	11 kg	72 kg	Very-low-mass sphere
	1.5	4	8 kg	31 kg	194 kg	Low-mass sphere
	1.5	10	21 kg	77 kg	485 kg	High-mass sphere
	3	5	5 kg	11 kg	20 kg	Very-low-mass sphere
Note: different	3	10	10 kg	21 kg	40 kg	Low-mass sphere
Structural ballast	3	20	20 kg	42 kg	80 kg	Medium-mass sphere
mass						
	6	30	17 kg	30 kg	45 kg	Low-mass sphere.
	6	80	45 kg	80 kg	120 kg	Medium-mass sphere.
	6	150	84 kg	149 kg	225 kg	High-mass sphere.

Table 69, Comparison of wind/ballast-propulsion performance; some examples.

Solar cells, Peltier elements and Micro turbines all produce electrical energy, that can be transformed in locomotion torque with electric motors. In case of Thistle-rover the internal ballast is the method to utilize these energy sources.

11.4 Hopping

Throwing a 50 kg ball on Mars to height of two meters would require 372.7 J energy. Some energy must be also reserved to give horizontal speed for the ball, since it is not the intention to bounce up and down at the same location. For a 2 meters high leap intial vertical speed would be –by the kinetic energy calculated above- 3.4 m/s. Time of flight can be calculated by the impulse and change of velocity. Since the gravity affecting on the ball is constant, time of flight (one-way) would be 3.4 m/s / 3.727 m/s^2, which makes 1 s one-way or 2 s until touch down.

A ballistic trajectory could start in a 45 degrees angle, in which case the vertical and horizonal velocities are equivalent in the beginning. If ignoring effect of atmosphere, during the flight the ball would travel horizontally four times the height, or 8 metres in this case. The ball would also have the initial vertical and horizontal velocities at the moment of landing. Vertical velocity would cause an impact on ball structure, while horizontal velocity would make the ball to rotate after touch-down. Practically all of the energy used for the leap would be lost upon touch-down and the following rolling.

Horizontal speed of the ball would equal to vertical speed, and so also the energy of horizontal motion would equal to energy of vertical motion. Thus overall energy needed would be double of that calculated by the height. That is, for a 2 meters high and 8 meters long leap 745 J energy would be needed.

As for an example we can take three pieces of extra-heavy tool springs with following properties:

Single spring properties			
Extra-heavy tool spring			
L0	303	mm	Spring length
c0	126	N/mm	Spring constant
Lc	106	mm	Maximum compression
od	51	mm	Outer diameter
id	25	mm	Inner diameter
Lmin	197	mm	Fully compressed length
Fc	13356	N	Maximum force
mo	1980	g	Mass

Table 13, An example spring for hopping action.

If we place these springs in series we can calculate the following properties for a spring assembly:

$$cn = \frac{c0}{n}, \quad Lcn = n \cdot Lc, \quad Fcn = Fc, \quad W\max = \tfrac{1}{2} cn \cdot Lcn^2$$

Spring assembly properties			
Extra-heavy tool spring			
n	3		Number of springs in series
Ln	909	mm	Length of spring assembly
cn	42	N/mm	Spring constant
Lcn	318	mm	Max compression
Lnmin	591	mm	Minimum length
Fcn	13356	N	Max force
Wmax	2123	J	Max energy
mn	5940	g	Approximate mass

Table 14, Example hopping spring assembly properties.

We see stored energy of 2 kJ, that would allow a 5.5 m high and 22 m long leap. Spring length would be 909 mm (591 mm fully compressed) and maximum force would be 13.4 kN. Mass of the spring only would be approximately 5.9 kg. A smaller 20-kg ball would hop 14 m high and 56 m long with a similar spring assembly.

A light tool spring used in a similar way would reduce the needed compression force to 6 kN, mass to 5500 g and energy to 1.4 kJ. This would allow a 9.5 m high and 38 m long hop for a 20-kg ball. A small-scale 10 kg device with a single light tool spring (303 mm in length) would perform a 6 m high and 24 m long leap with 6 kN max force. (For comparison, on Earth gravity the hop would reach 2.3 m height and 9.2 m distance.)

Internal loads on the system appear quite high, and for good hopping capabilities a trade-of between system mass and hop height/length must be made. Also system effciency and dynamic behavior upon release of spring energy must be studied. Sudden release of energy may cause unwanted structural deformation and loss of energy. A concept to tension and guide the spring, lock it and release it is a demanding technical issue.

11.5 Pushing

Instead of hopping high and over long distance, the ball could be gently pushed over small obstacles or out of a small pit. The ball could carry a telescopic push-stick that would extend with the aid of an electric motor and so would push the ball above obstacle with height 1-2 times of ball diameter. This kind of operation would protect the system from high internal forces and stored energy induced by any hopping mechanism. Also velocity of motion is better controlled.

Considering the motivation of a wind-propelled Thistle all the mechanics should be designed to be simple and of low-mass requiring minimum amount of energy, sensing and intelligence. Thus the push-stick should not be a leg or multiple legs intended for balanced standing or even walking, but a simple stick without any requirements for accurate sensing; otherwise the benefits of a simple Thistle rover would be lost. A telescopic push-stick could be located inside a central tube or ballast arm of the Thistle. If placed inside the ballast arm positioning of the push stick can be adjusted; provided that the stick is able to penetrate through the Thistle cover (possibly net-like or in other way open structure).

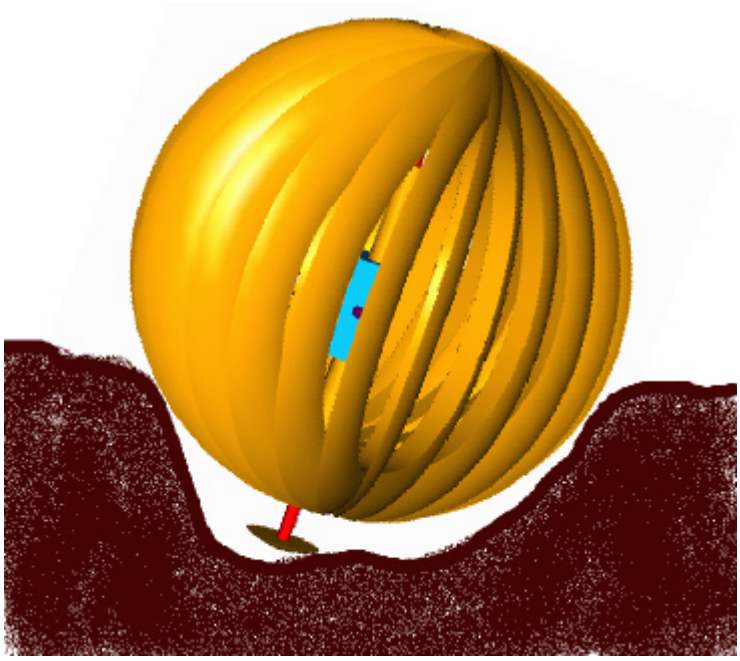


Figure 70, A telescopic push-stick elevates the Thistle out from a pit.

11.6 Conclusion of mobility considerations

As we at this moment do not know physical properties of the Thistle-rover to be constructed, we need to consider a few options. Note that internal ballast and tangential fluid ballast do not differ from each other in terms of mobility. Only the method to produce the off-balance is different. The ones to be taken into consideration from the sections above could be the following:

Thistle construction options			
	Size	**Mass**	**The best mobility**
1.	Small diameter (1.5 m)	Low mass (1.5 –4 kg)	**1a. Wind propulsion;** 0.4-0.6 m @ 32 m/s; (minimum requirement 15-20 m/s) **1b. Hopping;** (5-12 m high, 20-50 m long leaps) **1b. Pushing;** (1-3 m or 1-2 times ball diameter)
2.	Small diameter	Moderate mass (13-35kg)	**2a. Internal ballast;** 0.4 m (1.5-4 kg ball) **2b. Hopping;** (5-12 m high, 20-50 m long leaps) **2c. Pushing;** (1-3 m or 1-2 times ball diameter)
	Small diameter	Moderate mass (85kg)	**3a. Internal ballast;** 0.4 m (10 kg ball) **3b. Pushing;** (1-3 m or 1-2 times ball diameter)
3.	Medium diameter (3 m)	Low mass (5-10 kg)	**4a. Wind propulsion;** 0.6 m @ 15-21 m/s; (minimum requirement 10-15 m/s) **4b. Hopping;** (5-12 m high, 20-50 m long leaps) **4c. Pushing;** (3-6 m or 1-2 times ball diameter)
4.	Medium diameter	Moderate mass (16-30 kg)	**5a. Wind propulsion;** 0.4-0.6 m @ 30 m/s; (minimum requirement 16-24 m/s) **5b. Internal ballast;** 0.4 - 0.6 m (5-10 kg ball) **5c. Hopping;** (5-12 m high, 20-50 m long leaps) **5d. Pushing;** (3-6 m or 1-2 times ball diameter)
5.	Medium diameter	High mass (30-100 kg)	**6a. Internal ballast;** 0.4 - 0.6 m (10-20 kg ball)
6.	Large diameter (6 m)	Low- mass (30-60 kg)	**7a. Wind propulsion;** 0.6 m @ 14-20 m/s; (minimum requirement 10-16 m/s)
	Large diameter	Medium mass (60-160 kg)	**8a. Wind propulsion;** 0.6 m @ 22-30 m/s; (minimum requirement 16-22 m/s) **8b. Internal ballast;** 0.4-0.6 m (30 kg ball)
7.	Large diameter	High mass (160-375 kg)	**9a. Internal ballast;** 0.4-0.6 m (80-150 kg ball)

Table 15, Thistle locomotion options

The table above can be used to review possible locomotion methods and expected perfomance when ball mass and diameter are known. From the table we can see that for a

low-mass 1.5 m Thistle (or even smaller) hopping or pushing is the only way to overcome obstacles efficiently. Hopping and pushing can also be used for other ball sizes and masses up to 50 kg provided that the internal spring force can be handled. A 1.5 m ball with a 50 kg ballast would have a reasonable mobility.

A low-mass 3 m ball would be wind-driven, but in mass range 20-60 kg also internal ballast would be an option. In this range it would be useful for redundancy and versatility to design a such a mechanical structure that allows utilization of both locomotion methods. In the mass range 50-200 kg only internal ballast can be considered.

Combination of internal ballast and wind propulsion appears to be effective also for a 6-m ball. A 40-kg 6-m ball with 85 kg ballast (total mass 125 kg) would overcome 85 cm obstacles both with its internal drive and with 31 m/s wind.

With proper mass distribution between ball structure and ballast the obstacle overcoming capability can be similar for ballast-driven and wind-driven locomotion. If the instrument mass can be used as a ballast, adding a ballast-driven system to a wind-propulsion would improve operational capabilities of the Thistle. It is necessary to include a mechanism to locate ballast in a favorable orientation inside the ball for wind-driven rolling. However, if the ballast mass is a dummy mass without any scientific reasoning, pure wind-propulsion would be more beneficial due to smaller system mass.

For a purely wind-driven Thistle any ballast would add mass and thus reduce performance. However, adding the ballast would add a steering capability and independence of wind conditions. A proposed ballast-driven Thistle design could have a 3-m diameter, 20.5 kg ballast and 7-kg ball equipped with wind-turbine design. Obstacle overcoming capability would be 0.4-0.5 m with internal ballast drive or with 29 m/s wind. A 6-m 40-kg Thistle with a 85 kg ballast would still have a good locomotion performance and capability to overcome obstacles 80 cm high both with internal drive and with wind force.

Use of a liquid-ballast is justified only if autonomous locomotion independent from wind-conditions is desired. This is because the liquid adds mass and so reduces performance of a wind-driven Thistle, and the liquid is a dummy mass that can be replaced with useful payload for a lever-ballast or rail-ballast.

12 Mechanical Thistle concepts

12.1 Wind turbine

The wind turbine would be completely driven by the wind with little possibilities for steering. The turbine-shaped Thistle would resemble the JPL-developed Tumbleweed, except that the turbine-shape can improve response to wind load by approximately 25%

(11% less wind velocity is needed). The Thistle need not necessarily be of an open-section, as illustrated in artistic drawings below, but it can construct also of a closed volume (a balloon or similar) to protect the instruments from Martian environment.

Additional functions that can be installed for the Thistle would include re-orienting the ball with a movable mass inside the instrumentation tube, and anchoring the thistle on ground to be used as a wind mill. A movable mass would turn the Thistle and instrumentation tube into vertical position, and the anchoring system in the end of the tube would enter into ground. Now the turbine can rotate around the instrumentation tube and electricity can be produced with a generator. Energy production capability of a such thistle can be significant.

Caution must be paid for the mass of the system since added mass rapidly decreases locomotion capability of the Thistle. Also anchoring of the ball to the ground would be a challenging task. A sort of drill or harpoon should be considered and added mass would be several kilograms, unless there is a scientific drill already included in the system.

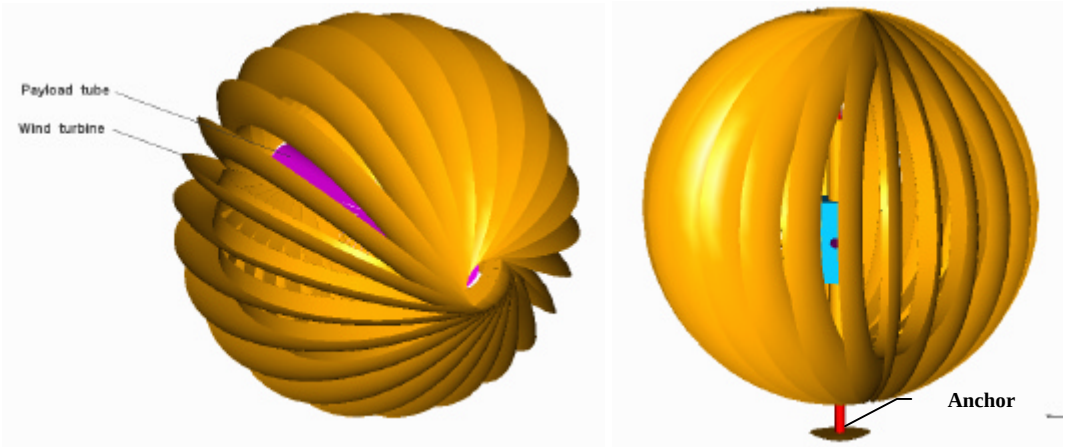


Figure 71, Wind-turbine Thistle rolling (left) and anchored for a wind mill operation (right).

12.2 Fluid ballast

The fluid ballast constructs of a series of circumferential shrink-tubes filled with fluid. Amount of fluid is 20-200 kg depending on Thistle mass and diameter. The shrink tube is constructed so that it shrinks in cold, and expands in hot. So the fluid inside the tube is collected on hot part of the tube, and off-balance develops. The resulting off-balance makes the ball to rotate and the rotation turns the heated part into shade and reveals a new part of surface to be heated. Shrinking and expanding of the tubes drives the fluid again towards the heated part of the tube.

The fluid itself should remain liquid in temperature range –80 C to +100 C and in Martian atmospheric pressure 700 Pa. The tubes can also be pressurized, but then leaks to atmosphere are more evident. Silicone oils and other synthetic oils, like lubricants developed for space use, can fulfill these requirements.

If we assume that fluid (20 kg) is to be collected on 90 deg. high illuminated area of a 3-m ball (10-kg sphere), tube length of this portion would be p/2 * 1.5 m = 2.36 m. If we assume expanded tube diameter 3 cm and fluid density 0.9 g/cm3, one tube would hold in the hot part 1665 cm3 or 1499 g fluid. Hence number of tubes in parallel should be 13 which, when 3 cm in diameter, would take 40 cm width or a 15 degrees wide sector. 13 tubes 1.5 cm in diameter in intial condition would hold the needed amount of fluid, but require complete shrinkage in cold and expansion to 3 cm diameter in hold to push all fluid into desired location. A larger tube with less shrinkage can be used, but then some fluid will remain in cold parts of the tubes as an unnecessary weight.

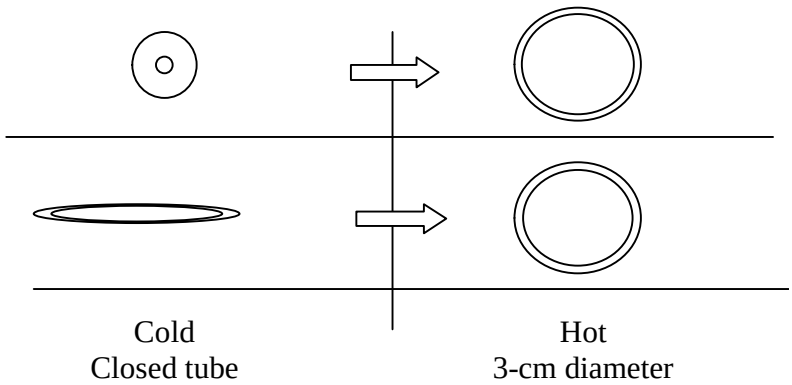


Figure 72, Operation of a shrink-tube pushing the fluid into hot areas (two options).

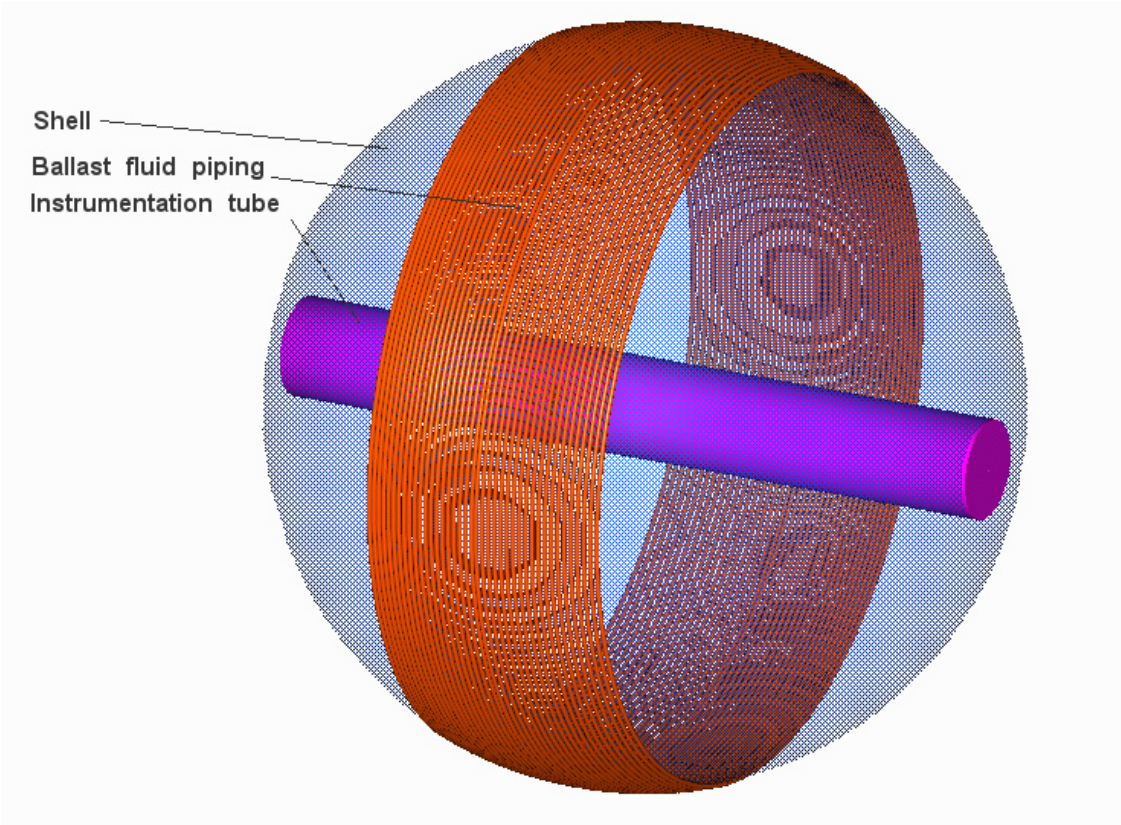


Figure 73, Fluid-ballast -type Thistle.

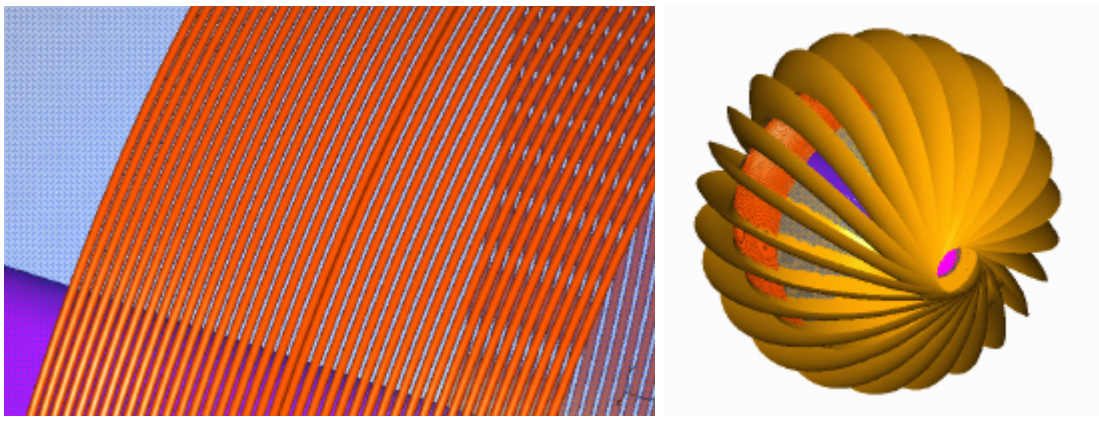


Figure 74, Detail of fluid ballast piping (left)
and a combined wind-turbine / fluid ballast Thistle (right).

It is not evident how this kind of a rover could be guided. The payload inside the instrument tube could be made movable, and so balance of the ball can be disturbed and it could be stopped by turning the tube into vertical position (the tangential fluid tubes in horizontal plane then). Even if there exists some ways to select orientation of the ball, it will in any case always roll towards the Sun.

Mobility of the ball can be assisted with added wind-turbine lay-out, as illustrated in image above.

12.3 Lever ballast

In this concept a rolling axis runs through the ball. A lever is mounted to the axis with bearings and a drive gear. A ballast mass mounts to the end of the lever. In steady position the ballast hangs right below the axis. As the roll motor is activated the ballast tries to elevate which makes the ball to roll around the rolling axis.

The concept would be most suitable for small-sized balls (0.5-3 metres). A 3-m ball is already quite big since the lever needs to be already roughly 1.5-m long. A long lever would ask for high motor torque and may also induce undesirable bending, flexibility and vibration into system.

The design does not include any means for steering. For steering purposes additional freedoms (and motors) must be implemented.

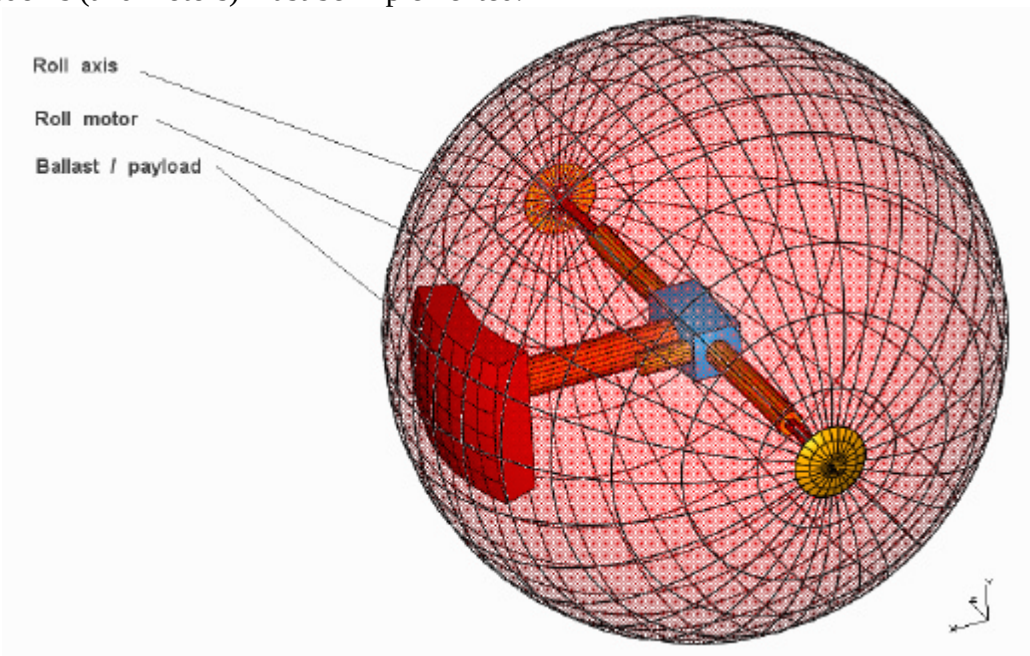


Figure 75, A Thistle with a lever ballast.

12.3.1 Double lever ballast

Steering capability can be implemented by dividing the ballast into two parts and adding another degree of freedom in the end of the lever. Now the angle between the lever and rolling shaft can be adjusted. See illustration below.

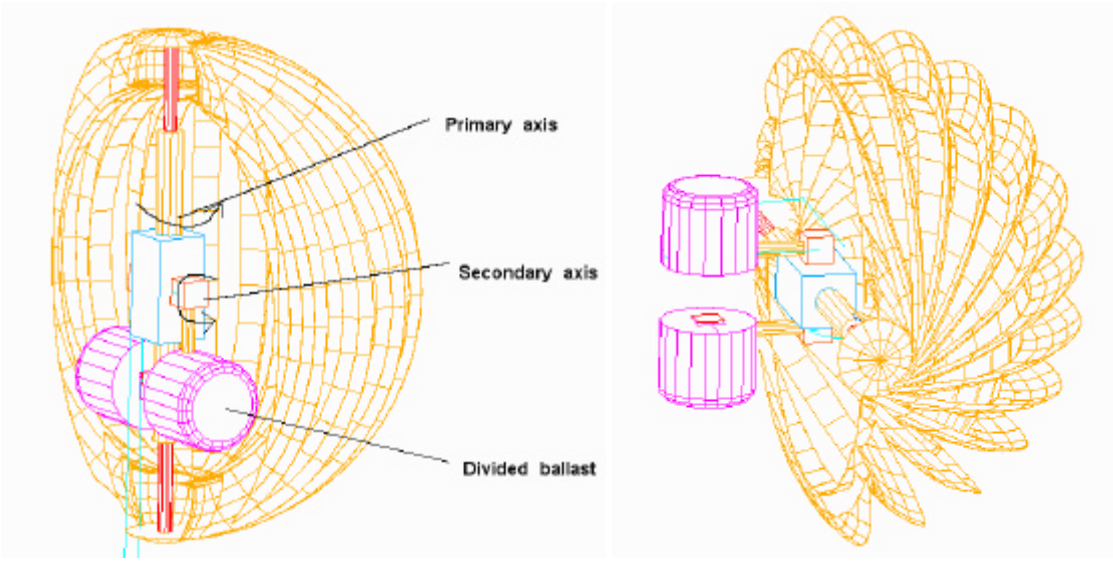


Figure 76, A Thistle with a steering ballast; turning position (left), rolling position (right). (Cut-away views).

When the lever is turned to be parallel with the roll shaft, the ball adopts a position where the roll shaft stands in vertical direction. Now the desired rolling direction can be selected by rotating the roll motor. As the lever is rotated to be in straight angle to the roll axis, the ball sets the roll axis into horizontal position. Now the roll motor rotates the ball into direction orthogonal to roll axis. Also two orthogonal rolling directions can be achieved by rotating either the rolling motor (primary axis) or the lever motor (seconadry axis).

12.3.2 Lever ballast motor torque and dynamic behaviour

A fundamental property of ballast arm system is the way it stresses the ballast motor. Consider the drawing below. The ballast motor is located in the center of the ball (mounted on ball axis of rotation). The ballast mass is located in the end of the ballast arm.

Length of the ballast arm is lm+lb. As the ball hits an obstale with height h, the ball mass generates a resistive torque (Fm x lm). The ballast mass generates an opposite driving torque (maximum possible illustrated in drawing) (Fb x lb). The ballast motor torque, however, is much larger than the ballast torque: motor torque is [Fb x (lb+lm)]. It can be

noted the motor torque is inefficiently used. This torque also stresses the ballast arm requiring reasonable strength and also stiffness to avoid unwanted vibrations.

Instead of using constant motor torque to drive the ballast, also dynamic behaviour of the ballast as a pendulum can be utilized. By a sequential correctly timed power input the oscillating ballast pendulum can collect a sufficient amount of energy to elevate into required hight, but requiring less motor torque. The oscillating motion would also cause the Thistle to move back and forth in front of the obstacle which can help in overcoming the obstacle, at least by introducing dynamic inertia of the Thistle motion.

As a solution for a more efficient motor use the ballast arm can be removed completely, the ballast mounted on a rail running along ball outer surface and the motor being a part of the ballast mass. The rail-ballast is to be introduced in the following chapter.

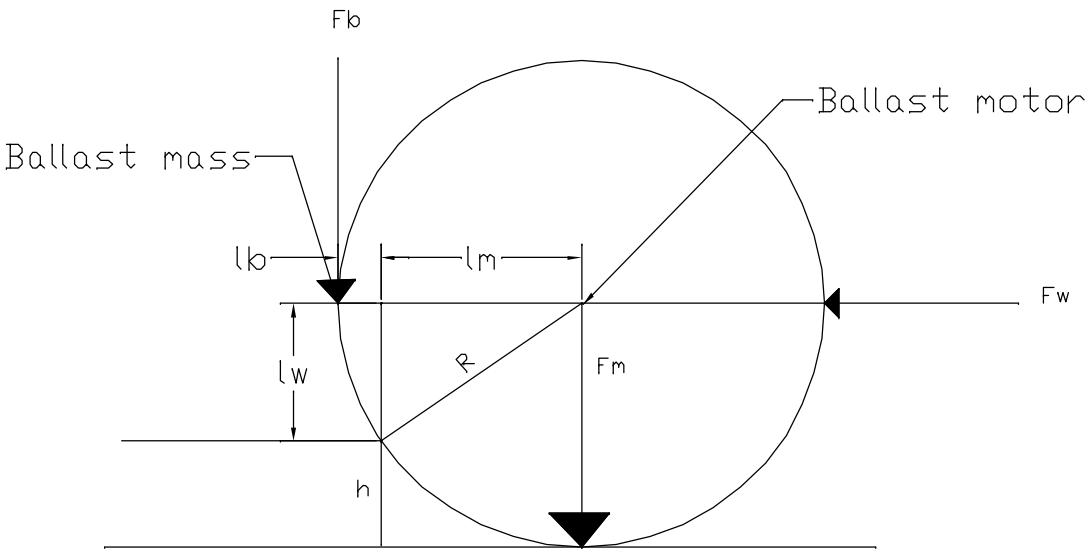


Figure 77, Ballast motor torque exceeds the driving torque.

12.4 Rail ballast

In order to avoid long levers inside the ball, the ballast can be mounted on a rail running around the ball inner surface. See illustration below.

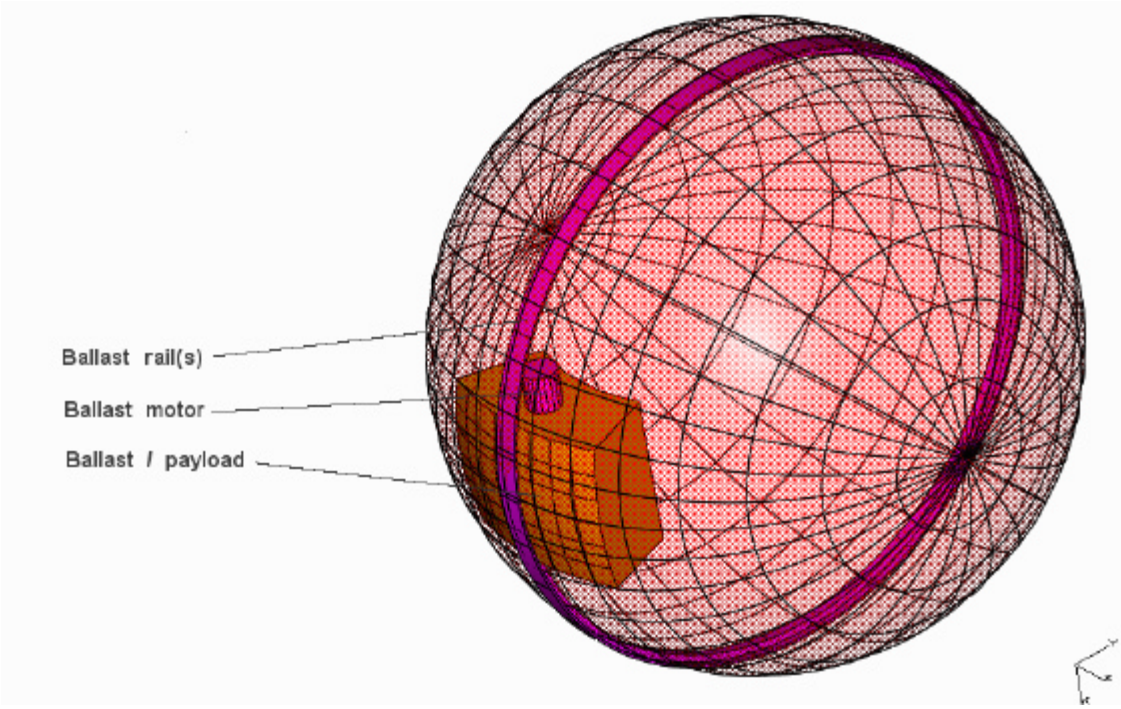


Figure 78, A ballast on a rail.

The concept resembles a guinea pig running wheel and several other old designs to develop torque from inside a wheel. Also the ball resembles a tracked vehicle, as it carries the pavement (the track, or the sphere in this case) along with it. Here the track maintains the spherical shape instead of running around two wheels. Like the single lever-concept this design does not include any means for guidance. A design with two ballasts on a single rail can be guided, as illustrated in pictures below.

12.4.1 Double rail ballast

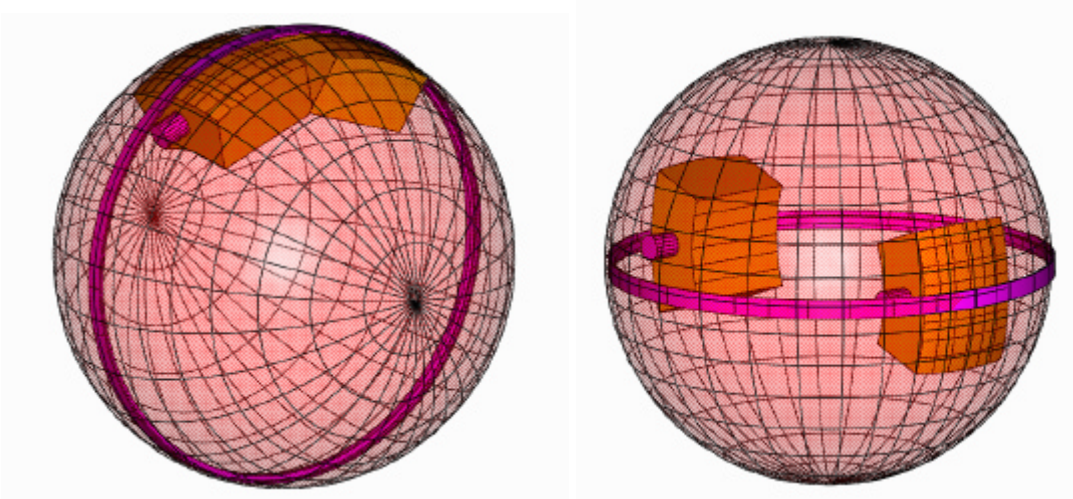


Figure 79, A double rail ballast in unstable position (left), and ready to choose direction for rolling (right).

When we have two ballasts we can imagine a procedure of synchronized movement that would end to an unstable position, as shown in illustration above left. As this position may start indepently rolling in any direction, it is also possible to gain a stable position illustrated in the illustration above right. From this position the two ballasts can be moved in a synchronized manner so that the rail ends up in vertical position and pointing into desired rolling direction.

12.4.2 Velcro-ballast

In order to avoid challenges caused by rigidity and accuracy requirements of a circumferential rail running on ball surface some additional constructions may be considered. One evolution of the previously-mentioned Rollo-robot consisted of a smooth ball and a 2-dof. roving vehicle running inside it. The vehicle had 4 wheels and it generated traction on ball inner surface purely based on friction. The vehicle, and so also the ball, had complete 2 independent degrees of freedom and it was easily rideable. A similar solution can be considered also for a larger ballast-driven ball. A 2-dof. rover can travel freely inside the ball and so guide the ball direction without limitations.

A flexible strcture, beneficial for a light system with large diameter, can not provide a good surface for high-friction wheel drive. Instead, the rover wheels could be coated with hooks of the Velcro-tape, and the ball inner surface with the loops containing fabric. Thus the rover with large flexible wheels could travel along flexible ball inner surface at high levels and so generate a high rolling torque. A challenge would be to choose proper materials to generate high enough holding force between the wheel and ball, but not too

high to tear the system apart and to consume too much energy in breaking the bond between the wheel and ball surface.

12.4.3 Lever ballast on rail

Imagine now that the two ballasts are connected to each other with a roll axis. A lever ballast is then hanging on this axis. We get a rail-carried lever ballast with two degrees-of-freedom. This steerable design has been developed and tested at HUT Automation technology laboratory for years already.

Figure 80, The Rollo-robot utilizes a lever ballast hanging on a rail.

12.5 Energy collection for ballast-concepts

The examples on ballast locomotion discussed above rely on electric motors. If we wish to utilize external power sources, we should transfer the collected energy for the motors. The sphere surface has a large area that would carry a large solar panel or array of Peltier elements. Energy from the panel or elements could be transferred for the control electronics and motors via slip-rings or current tracks and brushes mounted on axis-joints or rails. However, since the ball moves by rolling, the solar arrays and Peltier elements are endangered by Martian dust and external damages from terrain contact.

12.6 Thistle shape tarnsformation

It is seen favorable to have a possibility to tranform the shape of the Thistle.

A telescopic central tube of the thistle would by extending and retracting change the Thistle shape from horizontal oval to sphere to vertical oval. As vertically placed oval is not in stable position it would fall down and so change the orientation of thistle central tube from horizontal to vertical position. So orientation and also rolling direction of the Thistle can be changed.

Also rolling properties of the Thistle change when deformed and the rover could be parked on its place upon a command.

Folding for flight can utilize possibility to retract or extend the central tube. Extending may become in question if Thistle outer structure is to stretched to fit into a long and thin volume. Retracting can be useful is folding happens into minimun volume by nesting the outer structure on top of the central tube.

If the shell should have elastic properties, reshaping the structure can store some amount of energy. The central tube could be compressed with the aid of a string and a motor. Elastic energy of the reshaped shell can be suddenly released via the string into a hopping or pushing mechanism, or other mechanism that would need a large power for a short time.

The rail ballast system, however, may not be suitable with the telescopic central tube. The ballast rail is expected to be shape-accurate and reasonably stiff to allow smooth motion of the ballast mass along it. Changing the radius of the ballast rail may not be possible.

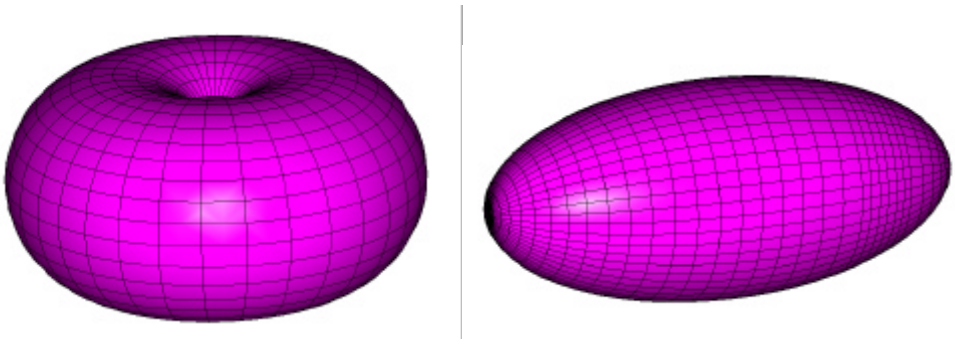


Figure 81, Two deformed shapes that are possible with a telescopic central tube. Donut (left) for parking, and oval (right) for folding.

12.7 Science instrument positioning

The Thistle is expected to study Martian soil and atmosphere.

Gases in atmosphere can be conducted inside the central tube through the poles of the open- or closed section Thistle. Thus the gas analyzing instruments may be located on/in

the central tube. In open-section Thistle the atmosphere is available also inside the Thistle and the instrumentation can be placed in the end of the ballast arm. Also gas line with a rotary joint between the central tube and ballast arm can conduct the gas to the ballast mass of a closed-section Thistle. Additional atmospehric sensors can be mounted on Thistle outer surface with electric lines running via central tube and ballast arm to the electronics.

For soil sampling an open-section Thistle with a ballast arm can lower the instrumentation against the ground with a telescopic arm. (See figure below left.) Additional sensors measuring soil surface properties can be mounted on running surface of the Thistle, being connected to the electronics as the atmospheric surface sensors. A 2-dof. ballast lever Thistle can be rotated so that the central tube ends into vertical position, another end lying against the ground. Now the instruments placed to the end of the tube can study the soil or anchor the Thistle for operation as a wind mill (see figure below right).

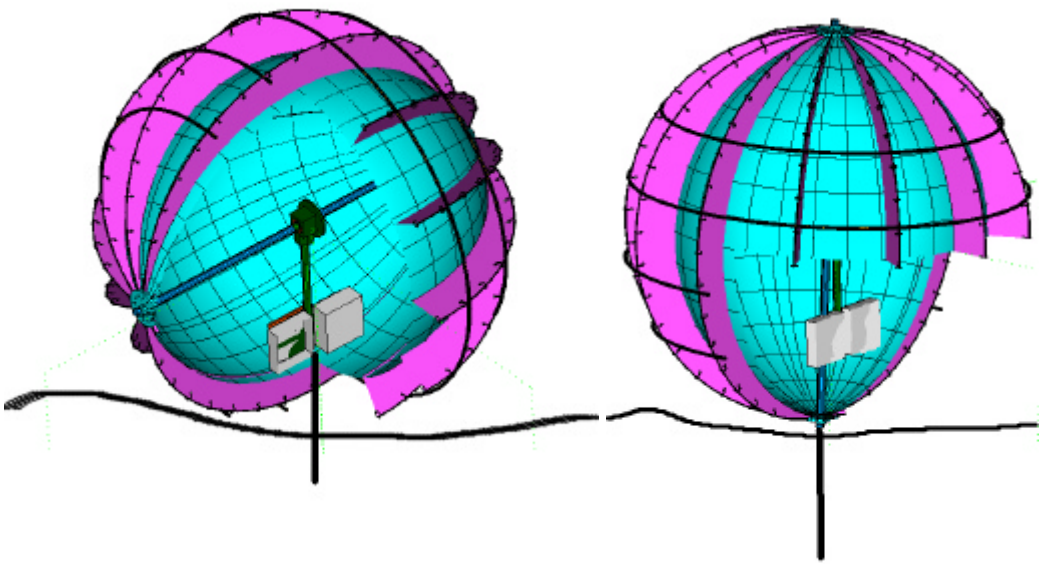


Figure 82, Cut-away views of a 2-dof. ballast Thistle in two possible soil sampling positions.

12.8 Pressurizing

Pressurizing of a closed-section Thistle adds rigidity of the structure. Further the closed section has higher wind resistance than the open-section. One solution could be to add the turbine blades on a pressurized closed-section Thistle. See images below.

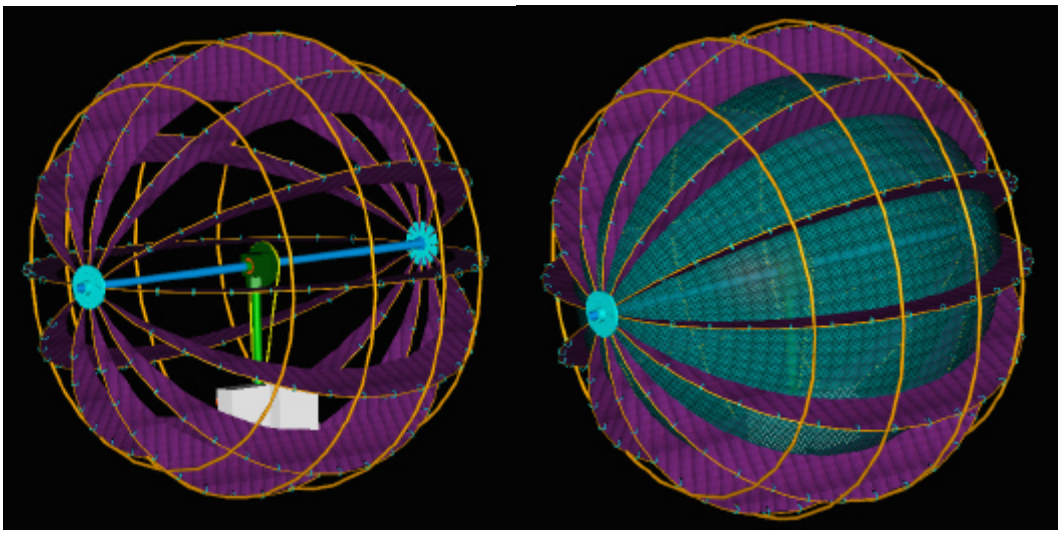


Figure 83, An open-section model (left) and a pressurized closed-section Thistle (right) with turbine blades and external skeleton.

13 Proposed Russian Thistle System description

13.1 Mechanics

The proposed Russian Thistle concepts is a combination of ballast drive and wind propulsion (see the illustration above). The Thistle consists of a central tube, a inner sphere of fabric (pressurization as an option), radial carbon fibre arcs for turbine blades (also from fabric), and tangential carbon fibre circles for added rigidity and smooth rolling. On the central tube is mounted a 2-dof. lever ballast, or alternatively a double-rail ballast runs along inner surface of the ball.

The lever ballast allows better control, operation as a generator and folding, but projects very high torque on the motor and lever. On Earth a 43-kg ballast mass with a 1.5 m lever would provide a 633 Nm torque on the ballast lever joint, the same torque also bending the lever and twisting the central tube. On Martian gravity the torque would be 240 Nm. This would require quite strong structures and target mass for the ball structure may become a limitation.

In case torque requirement becomes intolerable the double rail ballast (or velcro-ball) provides an alternative solution. The double rail ballast requires advanced rail structure which may prevent use of telescopic central tube and thus affect on folding.

Proposed Thistle properties are:

- Diameter 3 m.
- Ball mass 20 kg,
- Ballast mass 43 kg
- Total mass 63 kg

A larger 6-m Thistle would provide a better mobility and higher wind-resistance, but would require more demanding mechanical solutions.

13.2 Obstacle overcoming capacity

- 0.4 m obstacles with ballast drive
- 0.2 m obstacles with 35 m/s wind (assumes drag factor 0.8)

A larger Thistle would have better locomotion capability. A 6-m Thistle with a 40-kg sphere and 60-kg ballast (total mass 100 kg), would overcome 60-cm obstacles also with a 25 m/s wind thrust.

13.3 Scientific and payload instrumentation

Ballast mass (43 kg) allows a large number of instruments, also some heavy ones. A more strict limitation is the power requirement that limits to 10-30 W average. Some light-weight instrumentation can be mounted inside the central tube.

If ballast drive is omitted and the Thistle relies on wind propulsion only the sphere mass becomes critical (30 kg max.) and small and low-mass instruments should be selected.

13.4 Energy

- A 10-30 W average (8 hours per day) power production is expected with the aid of solar cells, peltier elements or wind-mill operation (optional).
- Local energy sources:
  - Advanced thin membrane solar cells
  - Advanced MEMS-Peltier elements
  - Collection of wind energy while rolling (using arm ballast and the motor as a generator).
- Batteries or RTG as an alternative for local power sources

13.5 Options

- Telescopic central tube
- Pushing mechanism
- Anchoring mechanism for operation as a stationary wind mill (possibly in conjuction with a drilling system.)

13.6 Operational capabilities

- Travel over smooth terrain propelled by wind
- Overcome obstacles with ballast drive
- Change traveling direction with a 2-dof. ballast drive
- Re-orient central tube in vertical position with the aid of 2-dof. ballast
    - In vertical position: examine soil, operate drill, anchor for wind mill operation, activate push stick for escape from a cavity (optional), extend an antenna
- With a telescopic central tube (optional) allow parking (tube contracted in vertical position) and/or folding (tube extended in horizontal position).

14 Conclusion and recommendations

This work has studied locomotion and energy production on Martian surface over a very large range of technologies. The final conclusion and system proposal is in large extent a conceptual and preliminary one. Relevance of the design was tried to maintain considering the Martian environment, examining real scientific instrumentation, and with theorethical calculations –added with some testing- on mobility. 3D-modelling reveals volumetric relevance.

Locomotion capability calculations presented here are based mostly on measured data on the rock distribution and wind velocity. Since wind conditions and rock-distribution may depend on location of the landing site, and wind-conditions also on landing time, propulsion consideration should be repeated when the time and place of landing is known. It must be considered what should be obstacle overcoming capacity by wind propulsion under expected local wind conditions, and what should be performance of the ballast drive.

Detailed mechanical design, strength, mass, mass distribution, motor dimensioning and folding deserve in future close attention in order to produce solid concept that could be realized and tested as a mechanical conseptual model or as a proof-of-principle. The conseptual prototype can be 1.5 metres in diameter, as atmospheric density on Earth is more than sufficient. The drawings below present anticipated construction of a simple 1-dof. Thistle.

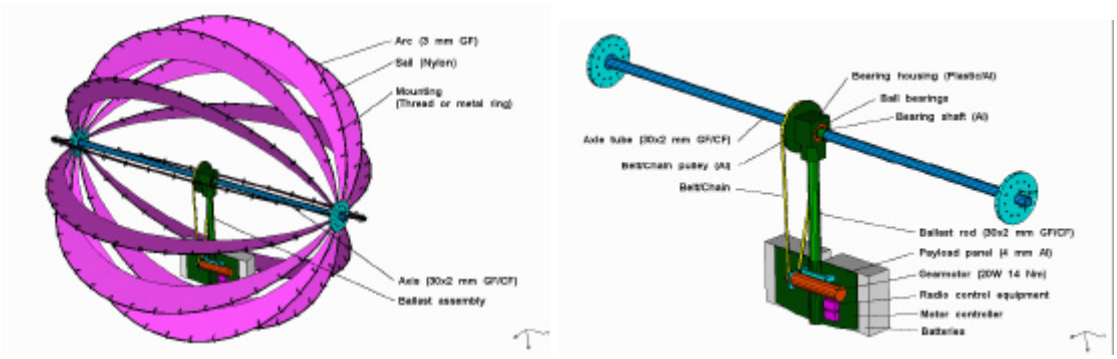


Figure 84, Possible configuration of a 1-dof. ballast lever Thistle prototype.

15 References

[RD 1] THE SEARCH FOR EARLY LIFE ON MARS: AN ESA EXOBIOLOGY SCIENCE TEAM STUDY. P. Clancy, A. Brack, B. Hofmann, G. Horneck, Gero Kurat, J. Maxwell, G. Gabriele Ori, C. Pillinger, F. Raulin, N. Thomas, F. Westall, and B. Fitton, Workshop on the Issue of Martian Meteorites

[RD 2] ESA ExoMars09 , CDF Study Report: CDF-14(A), August 2002

[RD 3] ESA Advanced concepts team home page, http://www.esa.int/gsp/ACT/

[RD 4] SPIE Proc. 5267, Intelligent Robots and Computer Vision XXI: Algorithms, Techniques, and Active Vision (Eds., D. Casasent, E. Hall, and J. Roning) , 27-31 October 2003, Providence, The expanding venue and persistence of planetary mobile robotic exploration—new technology concepts for Mars and beyond , Paul S. Schenker, Alberto Elfes, Jeffrey L. Hall, Terry L. Huntsberger, Jack A. Jones, Brian H. Wilcox, and Wayne F. Zimmerman , Jet Propulsion Laboratory, California Institute of Technology 4800 Oak Grove Drive, Pasadena, CA 91109-8099

[RD 5] The Planetary Society, http://www.planetary.org/mars/

[RD 6] NASA planetary sciences at the NSSDC, http://nssdc.gsfc.nasa.gov/planetary/lunar/apollo_lrv.html

[RD 7] Mars Pathfinder Rover, http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=MESURPR

[RD 8] NASA/JPL Mars Rovers, http://marsrovers.jpl.nasa.gov/home/index.html

[RD 9] Beagle home page, http://www.beagle2.com

[RD 10] NASA planetary sciences at the NSSDC, http://nssdc.gsfc.nasa.gov/planetary/mars_future.html

[RD 11] Development of the Tumbleweed Rover, Jaret Matthews, Robotic Vehicles Group, NASA Jet Propulsion Laboratory, Pasadena, California

[RD 12] Planetary Science from Directed Aerial Robot Explorers (DARE), Phase I Final Report, Global Aerospace Corporation, 2 December 2002 , Universities Space Research Association Research Grant No.: 07600-099 , GAC Report 510-09911-003 711 W. Woodbury Road, Suite H Altadena, CA 91001-5327 USA

[RD 13] PLANETARY MICROPROBES – DATA TRANSMISSION AND LOCALISATION SYSTEM FOR MICROPROBES SWARMS "DALOMIS", A. Schiele (TOS-MMA), TOS-MMA/2003/523, issue 4, 08th may 2003, ESTEC Keplerlaan 1 - 2201 AZ Noordwijk - The Netherlands

[RD 14] The DLR HRSC-Experiment web-page
http://berlinadmin.dlr.de/Missions/express/marsfacts/marsfactsheet.shtml

[RD 15] Mars physical and orbital statistics, comparisons,
http://www.student.oulu.fi/~jkorteni/space/mars/properties.html

[RD 16] The NASA National Space Science Data Center (NSSDC) Mars Fact Sheet
http://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html

[RD 17] CONCEPTUAL DESIGN OF A MARTIAN POWER GENERATING SYSTEM UTILIZING SOLAR AND WIND ENERGY, Amir Hemmat, Chi Nguyen, Bharat Singh, Keir Wylie, University of Houston, Presented at SECOND ANNUAL HEDS-UP FORUM, May 6–7, 1999, Lunar and Planetary Institute 3600 Bay Area Boulevard, Houston, TX 77058-1113

[RD18] The Martian Climate Database
http://www-Mars.lmd.jussieu.fr/

[RD 19] ROCKS AT THE PATHFINDER LANDING SITE, MARS: IDENTIFICATION AND SIZE DISTRIBUTION. E. Hauber, R. Jaumann, C. Mosangini, N. Russ, F. Trauthan, K.-D. Matz, O. Fabel, DLR, Institute of Planetary Exploration, Rudower Chaussee 5, D-12489 Berlin-Adlershof, Germany (Ernst.Hauber@dlr.de).

[RD 20] NASA Quest
http://quest.arc.nasa.gov/mars/events/wwprimer.html

[RD 21] Mars Pathfinder Historical Weather Data
http://mars.sgi.com/ops/asimet.html

[RD 22] Reaching for Mars, NASA MARSPORT DESIGN COMPETITION 2002, Mars Deployable Greenhouse, Gary Ballmann et. Al, University of Central Florida/Florida Space Institute, 12424 Research Parkway, Suite 400, Orlando, FL 32826
http://mmae.ucf.edu/~aiaa/greenhouse/DDR_final-report-greenhouse.pdf

[RD 23] On-board Power Sources for Mobile Robots, V. Gromov, S. Matrossov, V. Petriga, Science and Technology Rover Company Ltd, Russian Mobile Vehicle Engineering Institute, 2 Zarechnaja Street, 198323, St. Petersburg, Russia, ASTRA 2002,

Advanced Space Technologies for Robotics and Automation, 19-21 November, 2002, ESTEC, Noordwijk, The Netherlands, pp. 307-314

[RD 24] Mars Exploration Rover Landings Press Kit, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION , January 2004

[RD 25] Actuator Design Using Shape Memory Alloys, 2. ed., Tom C Waram, 1063 Kng St. W., Suite 204 Hamilton, Ontario L8S 1L8, Canada, 1993

[RD 26] The VT1 Shape Memory Alloy Heat Engine Design, Jillcha Fekadu Wakjira, Thesis submitted to the Faculty of, the Virginia Polytechnic Institute and State University, January 2001, Blacksburg, VA

[RD 27] JPL Thermoelectrics Website, Thermoelectric Science and Engineering, http://www.its.caltech.edu/~jsnyder/thermoelectrics/history_page.htm

[RD 28] Jagdish U. Patel, Jean-Pierre Fleurial, G. Jeffrey Snyder, and Thierry Caillat, Miniature Radioisotope Thermoelectric Power Cube, Caltech for NASA's Jet Propulsion Laboratory, Pasadena, California. www.techbriefs.com/tsp NPO-30328 under the Physical Sciences category

[RD 29] Micro Electric Machines for Micro Turbomachinery, J. L. Steyn (C. Livermore, R. Khanna, J. H. Lang, S. D. Umans, and E. P. Warren in collaboration with A. H. Epstein and M. A. Schmidt, and A. Forte, T. Lyszczarz, and J. Yoon of MITLL), http://www-mtl.mit.edu/mtlhome/mems/powermems.shtml

[RD 30] The Bacterial Flagellum, Michael J. Behe, 1998, http://www.arn.org/docs/mm/flagellum_all.htm

[RD 31] Stomatopod Biology, A. San Juan, March 7,1998, http://www.blueboard.com/mantis/bio/wheel.htm (Partly adapted from Full R, Earls K, Wong M, and Caldwell R. (1993). Locomotion like a wheel? Nature 365, 495.)

[RD 32] A Novel Antipredator Mechanism in Salamanders: Rolling Escape in Hydromantes platycephalus, MARIO GARCÍA-PARÍS AND STEPHEN M. DEBAN, Museum of Vertebrate Zoology and Department of Integrative Biology, University of California, Berkeley, California 94720, USA, Journal of Herpetology, Vol. 29, No. 1, pp. 149-151, 1995 Copyright 1995 Society for the Study of Amphibians and Reptiles

[RD 33] Hop David, P. O. Box 39, Ajo, Arizona 85321, USA http://www.clowder.net/hop/curlups/curlups.html

[RD 34] "The Robot Zoo", Clear Channel Exhibitions, 4714 Industry Park Blvd. San Antonio, TX, 78218
http://www.thetech.org/exhibits_events/traveling/robotzoo/about/grasshopper.html

[RD 35] Sandia National Laboratories, Intelligent Systems and Robotics Center (ISRC), http://www.sandia.gov/isrc/Hoppers.html

[RD 36] Planetary Exploration Using Hopping Robots, Mirco Confente*, Claudio Cosma*, Paolo Fiorini*, Joel Burdic**, * University of Verona, Department of Informatics, Strada le Grazie 15, 37134 Verona, Italy, ** California Institute of Technology, Mechanical Engineering, Pasadena, California 91125, USA, Proceedings of Advanced Space Technologies for Robotics and Automation ASTRA 2002, 19-21 November 2002, ESTEC, Noordwijk, The Netherlands, pp. 369-376

[RD 37] DesertUSA.com, Digital West Media Inc., P.O. Box 270219, San Diego, CA 92198-0219, USA, http://www.desertusa.com/mag01/may/papr/tweed.html

[RD 38] NASA Glenn Learning Technologies Project, Aerospace Education Services Project, Oklahoma State University , http://www.grc.nasa.gov/WWW/K-12/TRC/Aeronautics/Maple_Seed.html

[RD 39] Queen's University, Math@Home, http://educ.queensu.ca/~fmc/november2003/november_20.html

[RD 40] Marshall, William, St. Francis Xavier University, Nova Scotia, Canada, http://www.stfx.ca/people/bmarshal/201/terrestrialloco.html

[RD 41] Hölldobler B., Wilson E. O.: The Ants, Belknap Press, 1990.

[RD 42] Dudek G., Jenkin M., Milios E., Wilkes D.: A Taxonomy for Swarm Robots, Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Yokohama, Japan, pp. 441-447, 1993.

[RD 43] Stilwell D. J., Bay J. S.: Toward the Development of a Material Transport System using Swarms of Ant-like Robots, Proceedings of the IEEE International Conference on Robotics and Automation, Atlanta, USA, pp. 766-771, 1993.

[RD 44] Deneubourg J.-L., Theraulaz G., Beckers R.: Swarm-Made Architectures, Toward a Practice of Autonomous Systems (Proceedings of the First European Conference on Artificial Life), Varela F. J. and Bourgine P.(Eds.), The MIT Press, Cambridge, Mass., pp. 123-133, 1992.

[RD 45] Fukuda T., Ueyama T.: Cellular Robotics and Micro Systems, World Scientific in Robotics and Automated Systems -Vol.10, World Scientific, 1994.

[RD 46] Brooks R., Flynn A.: Fast, cheap and out of control: A robot invasion of the solar system, Journal of The British Interplanetary Society, Vol. 42, pp. 478-485, 1989.

[RD 47] Murphy R.: Marsupial Robots, Robot Teams – From Diversity to Polymorphism, Balch T. and Parker L (eds.), A.K.Peters Ltd., Canada, 2002.