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Biologically inspired solutions for robotic surface mobility

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INTRODUCTION

The application of biomimetic locomotion to the Martian surface offers the possibility of increased robustness and failure tolerance. This study, funded by ESA/ESTEC under ARIADNA-program, focused on new innovations from nature 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 in context of surface properties of the target planet as well as power generation methods that would utilize local power generation resources like wind or heat. 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. Surface geography and roughness, presence of stones, cracks or soft sand set requirements for robot’s mechanical locomotion capability and navigation capabilities. 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. To be 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 largest rocks or cracks, like an elephant).

This study collected and discussed several locomotion methods found in nature (other that ambulatory walking, that is being studied separately). These include jumping, flying, gliding, floating (in air or in water) and rolling. Rotary motion, while so rarely utilized in nature, stole a large share of interest as several interesting natural examples were identified. Encouraged by our earlier experience on mobility of ball-shaped robots and efficient spreading of the plant called ‘russian thistle’ the study finally focused on locomotion and energy production for a ball-shaped systems imitating the russian thistle–plant. Among locomotion issues also energy production using local energy sources –having Mars as a target planet- were discussed. Local energy sources varying from solar light to heat radiation and atmospheric winds were examined and technical solutions utilizing solar panels, Peltier-elements, micro turbines, shape-memory alloys, wind-mills, wind-thrust, osmosis and heat-induced flow of liquid or gas were studied.

This article collects the results of study related to the Russian Thistle-type wind-propelled locomotion system (later called Thistle).

REFERENCE PROJECT: JPL TUMBLEWEED

Idea of copying Thistle-type locomotion for an artificial exploration device is not a new one; Jet Propulsion Laboratory (JPL) has built and tested a 1.5 m inflatable ball that was driven by the wind in a similar manner as the russian thistle, known as “tumbleweed” in USA [1]. Fig. 1. (Courtesy NASA/JPL) presents the inspiring plant and the roving system. The Tumbleweed robot has been demonstrated and tested successfully in small 1.5 m diameter scale on deserts and Antarctica. The Tumbleweed is basically a large pressurized beach ball that is carrying an equipment-tube on its horizontal rolling axis. The equipment measure temperature and composition of ambient air that is conducted in through the ends of the tube. The system also controls its internal pressure with the aid of air pumps, keeps track on its position with a GPS-equipment and communicates with a stationary ground station. While its mobility is dependant on the wind, the Tumbleweed rover has some ability to control its speed by regulating its level of internal pressure. A 6 meter diameter Tumbleweed could be released on the surface of Mars. The Martian Tumbleweed would include 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.

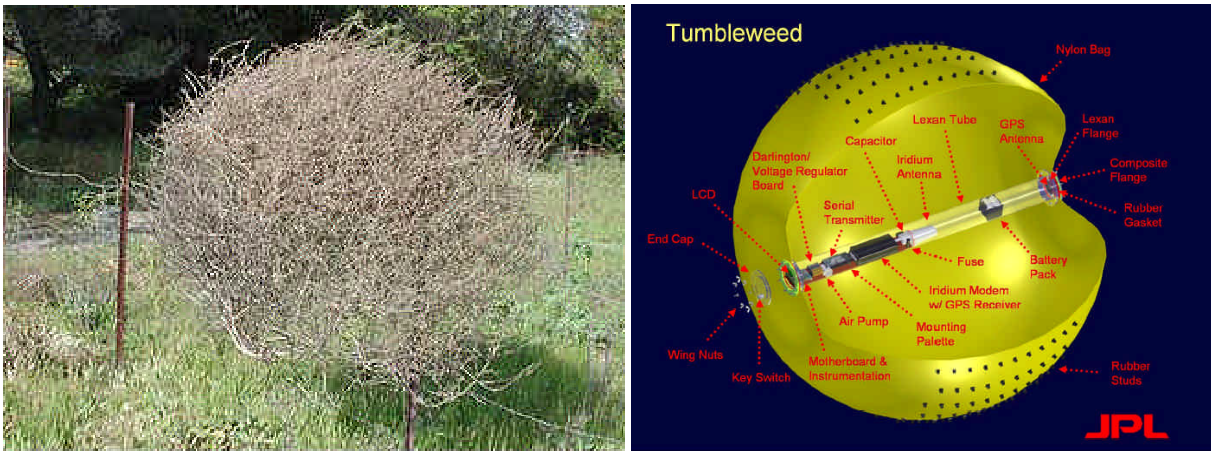

Fig. 1, The tumbleweed plant and inspired Tumbleweed Rover developed at JPL.

BALLAST-DRIVEN BALL-SHAPED ROBOTS

Fig. 2. presents a mobile ball-shaped robot ‘Rollo’ being developed at Automation Technology Laboratory of Helsinki University of Technology (HUT) already over several years. 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 (later called ballast) 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 companion at office or home. 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. Currently 15 cm and 45 cm variants of the original 30 cm Rollo are being developed at the lab.

Another ball-shaped device depicted in Fig. 2. is a toy called “Squiggleball”. Squiggleball, driven by an AA-battery, wanderers around floor and with an amazing capability gets around almost any obstacle. The Squiggleball motion is also based on ballast drive, as shown in the figure. Although completely lacking any intelligence, sensing or navigation, toy’s ability to move around in a labyrinth is so surprising, that audience watching the performance have been inquiring us what kind of navigation algorithm we are using. Answer is: none. One important feature of the ball is the rubber band running around the ball. 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. Behavior presented by the Squiggleball appears quite suitable for long-lasting exploring of planet surface without any external supervision and with minimized use of power consuming and failure susceptible guidance system.

MOTIVATION

The Tumbleweed demonstration model is a very sophisticated and advanced one. The structural composition with a pressurized ball suits very well for the intended application and provides locomotion capability and mass efficiency that is hard to be improved any further. It is not our intention to re-invent the Tumbleweed, but we wish to study, if there are possibilities to improve or add robot’s capabilities, especially in terms of steering and power generation. Our approach was to study first aerodynamics of the ball, then power collecting methods on Mars and finally see if there is a meaningful way to combine properties of the Tumbleweed and ballast-drive to produce a steerable autonomous ball-shaped Mars-exploring robot.

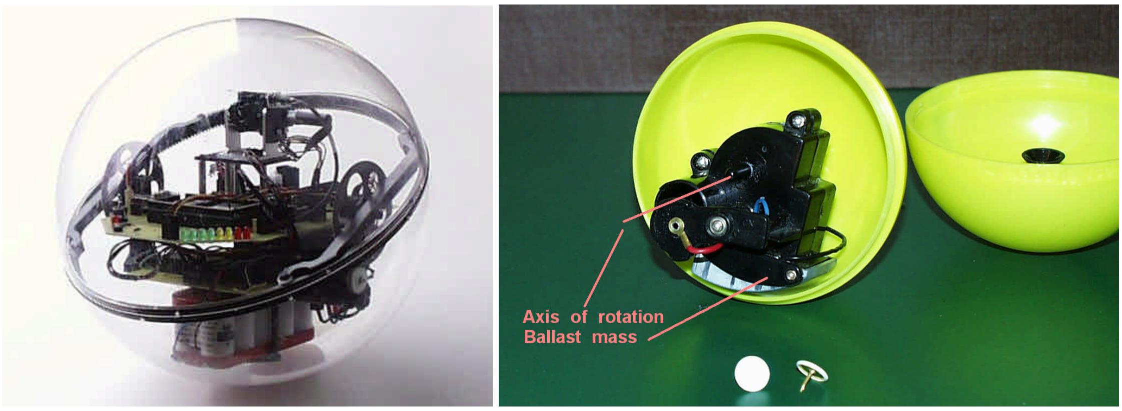

Fig. 2, Two ballast-driven devices: Ball-shaped robot Rollo (HUT) and Squiggleball.

AERODYNAMICS

We wish to study if re-forming ball surface into form of a wind-turbine would increase ball's resistance to wind and so improve locomotion capability of the robot. A single active force affects the rover:

$$F = kArv^2 \tag{1}$$

The force acting upon the sphere is due to the drag of air, which is a function of the shape. For a 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*. (These coefficients vary slightly by the sources.) The air density ρ can be taken for ρ =0.02 kg/m^3 for Mars, and ρ =1.29 kg/m3 for the air on Earth. Equivalent aerodynamic situation can be modeled on Earth if we scale down the diameter of the ball to account the ratio between atmospheric density on Earth and on Mars:

$$r_E / r_M = 1.225 / 0.02 \approx 61 \tag{2}$$

Thistle obstacle overcoming capability depends on its cross-sectional area that feels the wind, and it's diameter that defines the torque the force generates. Thus motion torque is cubic of the ball diameter. If atmospheric density decreases by a factor shown in (2), the ball diameter must increase in cubic root to maintain same locomotion torque generated by the same wind velocity:

$$\sqrt[3]{61} \approx 4 \tag{3}$$

So for a given wind velocity a four times bigger 6 m Thistle on Mars would have a similar locomotion torque as its 1.5 m little brother on Earth. Fig. 3. gives qualitative picture of these forces for the NASA Tumbleweed on the Earth and for a 6 m Russian Thistle on the Mars. Note the dominant factor of the wind speed and a minor factor of the shape factor. It can be seen that drag itself is quite small on the Mars, even though it will be compensated by a larger moment-arm of this force. The ~ 20 kp force on the 12 m/s wind and a small *k*~ 0.5 can move the ball with a relatively high speed on Earth. A hypothetical 6 m diameter ball on Mars experiences a ~ 5 kp drag force at 10 m/s wind. At 20 m/s high speed storm the drag is ~ 15 kp. If we consider the drag-force alone, without paying attention to torque moment-arm, the drag force increases in square of the ball diameter. Hence, if atmospheric density decreases as stated in (2), the ball diameter must be increased in square root of (2), which is 7.8 fold. So for a given wind velocity an 11.7 m ball on Mars would feel the similar drag as a 1.5 m ball on Earth.

We wish to examine if drag force can be increased with special shape of the ball surface. By adding turbine blades on the ball we change the ball coefficient of drag and also we add some more surface area where the wind can hit, as shown in Fig. 4. (left). Initial calculations show a very small advantage of turbine blades in terms of increased surface area but change of drag coefficient was indicated with an empirical test.

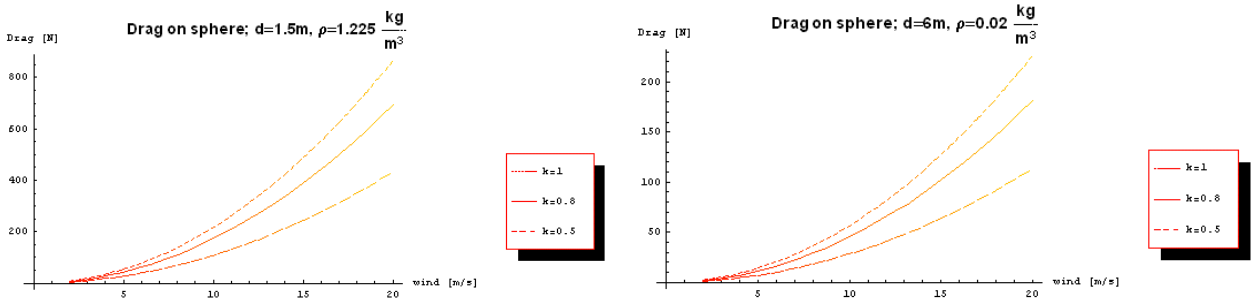

Fig. 3, Calculated drag on the NASA Tumbleweed on Earth, and 6 m Russian Thistle on Mars.

Drag Force Measurement Test

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. Six pockets were constructed and cross-sectional area of each pocket measures 10% of ball cross-sectional area. See Fig. 4. for test set-up. The test system allows measurement of the ball drag force and also ball rotation torque for the turbine-design. 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, as illustrated in Fig. 5. Relatively low wind velocity was used for the test.

The test was run with three different blower power settings at two different distances from the blower. 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 (1.66 m, low wind velocity) the benefit of the turbine layout appears even more favorable exceeding 70%. The resulting torque on the turbine ball appears quite low. Fig. 6. presents the test results with two analytical graphs with different coefficients of drag. An undesired peak at 3 m/s velocity resulting from measurement inaccuracy is visible. Wind load on turbine-shaped ball appears very promising compared to a plain ball; 10-20% increase in cross-sectional area increases ball drag force 60-70%. Overall coefficient of drag is surprisingly low, possibly due to low wind velocity and uneven velocity profile. Further experimentation is necessary with higher and continuous wind velocity. Another area of study is implementation of the turbine-design. Adding turbine blades on ball surface removes the spherical shape of the ball and affects on its rolling capability. Development work must be conducted to introduce mechanical design that allows smooth rolling also for the ball with a turbine design.

BALLAST DRIVEN THISTLE

As described earlier, a ball-shaped robot can be successfully constructed and guided and it also presents many interesting benefits in terms of locomotion. The ball-robot can not fall over, it can change its traveling direction on its place, it does not have any sharp edges, corners or extensions that might get stuck etc. While the JPL Tumbleweed presents quite an optimal mechanical solution in terms of strength and low-mass, it is clear that any added functions, motors and guidance would increase overall mass of the system. Mass increase is very critical when considering robots

Fig. 4, Artistic vie of a turbine ball (left), and a test set-up for a comparative wind force measurement.

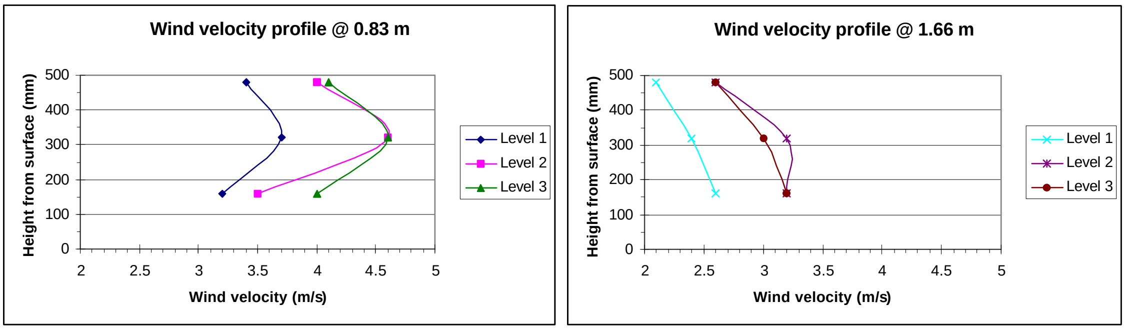

Fig. 5, Measured wind-velocity profiles.

locomotion propelled by the wind. Under Martian thin atmosphere the question is extremely critical. However, the Thistle will carry some instrumentation, power systems, communication systems and other vital equipment in every case. This mass can be used as a ballast mass for the ballast driven robot with only little added weight from the motors and related subsystems. We wish to study if there is such composition that would allow both approaches: to have redundant propulsion force either from Martian wind or from Thistle internal motors. To solve this we need to consider ball diameter, wind drag, overall mass and ballast mass all together and calculate resulting locomotion capability. Criteria for accepting a certain composition include expected wind velocity, expected obstacle size, reasonable size of the system and reasonable mass of the system.

Fig. 6. (right) presents the forces acting on Thistle. The symbols used are the following: *Fw* = wind drag, *Fm* = ball weight, *Fb* = ballast weight (at maximum, illustrated here located at ball radius *R*), *h* = obstacle height. Other symbols are used for calculations only and can be derived from the geometry. The geometrical calculations, being trivial, are omitted here. With the given information on ball diameter, ball mass and ballast mass we can calculate the needed wind velocity to overcome the given obstacle. We can also calculate size of the obstacle that can be passed over with the given ballast mass. If we put this information in one single graph, we can compare performance of both locomotion methods. Fig. 7. presents two charts, each showing two graphs. The uppermost graph shows how much wind velocity is needed for a ball with given mass to overcome an obstacle of 40 cm height. Respectively the lower graph shows the needed ballast mass to overcome a similar obstacle. One needs to check whether the required wind velocity is reasonable, and/or if the ballast mass is low enough to allow reasonable mass for the other ball structures. The leftmost chart shows that only a 1.5 kg 1.5 m thistle would pass over a 40 cm obstacle with the aid of wind drag. Also a similar 20 kg Thistle would need a 19 kg ballast for the same obstacle, which leaves only 1 kg for the other structural parts, which is quite little. A heavy 50-90 kg ballast-driven ball could overcome this obstacle, provided that majority of the mass is located in the ballast. On the other hand, as the chart on the right shows, a 6 m 20 kg Thistle would pass the 40 cm obstacle with a reasonable 10 m/s wind velocity. Also, if 10 kg is reserved for the ball structure and 10 kg for the ballast, the Thistle can travel over similar obstacles also with the ballast drive without compromising performance under windy conditions. Both approaches are applicable until Thistle total mass causes needed wind velocity to exceed any expected value. The ballast drive has not any upper limitation, and lower limitation is set by the minimum possible mass of the ball structure. The calculations can be repeated for different obstacle sizes and different Thistle diameters. It is then possible to decide case-by-case whether it would be useful to utilize an active ballast drive in addition to wind-propulsion. In general the active drive can be seen as an added value, unless total mass and system complexity increases too much due to added mechanical subsystems.

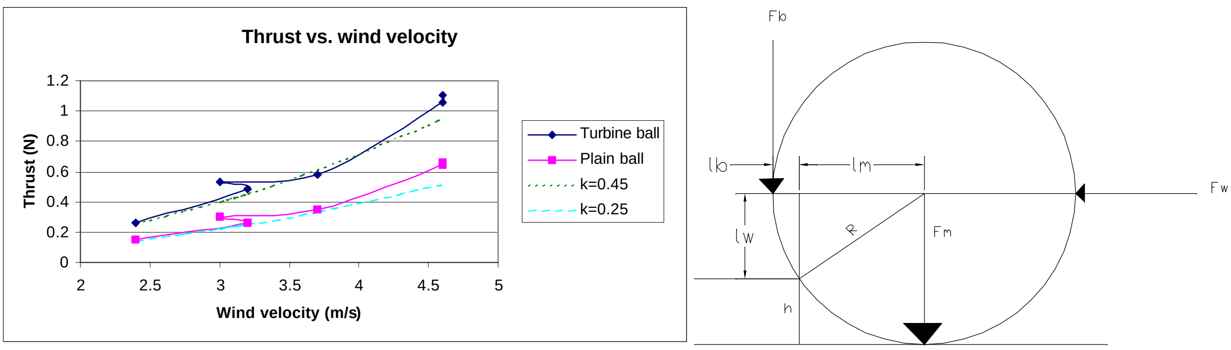

Fig. 6, Ball drag-force measurement results (left) and forces acting on a Thistle (right).

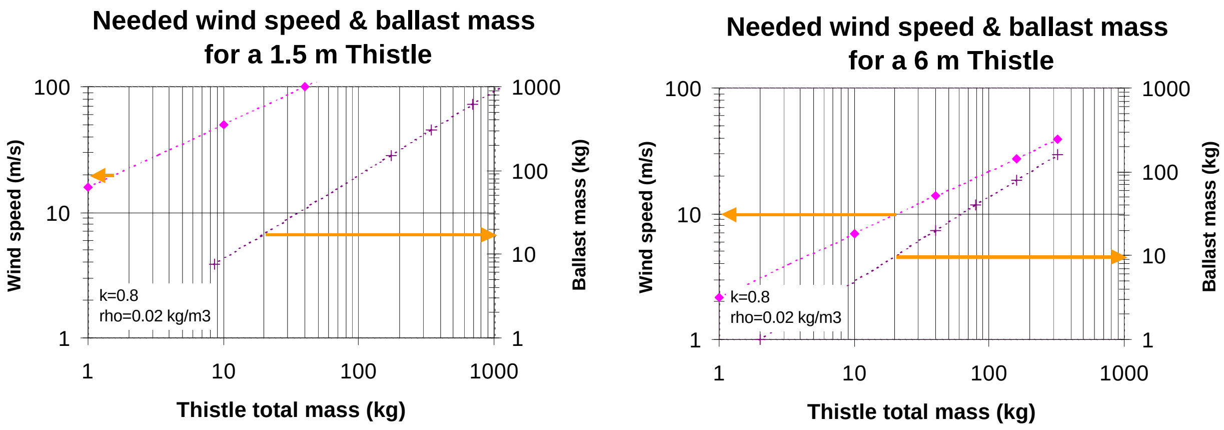

Fig. 7, Needed wind velocity or ballast mass to overcome a 40 cm obstacle on Mars.

LOCAL ENERGY SOURCES

Study on local energy sources is linked strongly to locomotion concept. First of all the locomotion concept defines the platform that carries the energy production equipment (the rolling ball is not necessarily a good basis for a wind-mill). Secondary some of the local energy sources can be utilized directly for powering the locomotion (like the wind pushing the Thistle). In addition to producing locomotion energy, the local energy sources may provide power for robot household, thermal control, communications etc. For these purposes energy must be usually converted to electricity.

Direct Propulsion

“Direct propulsion” here means that external energy sources directly make the robot to move. Martian wind presents a suitable energy source and above discussed wind drag is such force to move the robot. An alternative way to utilize the wind is a windmill that can directly drive a rover via mechanical coupling –as presented in [2]- or produce electricity with a generator. Another identified method for direct propulsion is utilization of heat energy. Diurnal variation in temperature, as well as temperature difference between ground / air / sky or temperature difference between sunny side and shaded side of the robot can be used to activate many kinds of thermal motion. Shape memory alloys and bimetals can change shape, deform the ball structure or relocate ballast mass in order to make a ball to rotate. Heating of gas or liquid causes expansion and pressure difference that in turn generates gas flow or liquid flow. Flow of liquid can be also generated with heat-induced concentration gradient of a solvent and osmosis. Energy from gas flow can be collected with miniature turbines as presented in [3]. Flow of liquid causes transfer of mass, which can be used to relocate ball center-of-gravity (cog) and so to make the ball to rotate. Heat induced direct propulsion turned out impractical, as areas of a ball-shaped robot to be heated cannot be effectively selected and unbalancing mass (that finally generates the motion) must be present everywhere over the surface. This makes the ball heavy and locomotion torque ratio low. The case can be different, if a different and more solid type of rover platform is selected. For details the interested reader is invited to refer to [4].

Production of Electricity

In production of electricity the above-mentioned wind mills and miniature turbines add to conventional solar cells and Peltier-elements. A comparison between different energy sources was performed keeping a 6 m Thistle as a target system. Table 1. presents the comparison. The results can be considered only as indicative since technical, geographical and seasonal factors affect on system performance in a large extent. For details the interested reader is again invited to refer to [4]. Solar panels and even Peltier-elements present conventional and familiar technology that appears quite superior compared to any other methods. Spherical shape of Thistle does not support efficient use of these systems as only a fraction of elements are active, and they are also vulnerable for damages during locomotion. However, advantages of cell technology and MEMS-technology may soon provide thin, flexible, durable and light solar panels and Peltier-element blankets that could be utilized also for Thistle-type rovers. A windmill provides a technically solid solution. Power output is very limited for small mills, but very large mills can produce significant amounts of energy.

Table 1. Electricity generation comparison

Method	Power	Energy	Notes
Solar Panels	1 084 W	520 320 W-min /sol	6 m ball, 25 % surface illumination, 8 hr sun visibility, 12 % efficiency, solar flux 320 W/m2
Peltier elements	452 W	216 800 W-min / sol	6 m ball, 25 % surface illumination, 8 hr sun visibility, 5 % efficiency, solar flux 320 W/m2
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

A challenge is to find a good base for a windmill on a roving vehicle. Surely a Thistle cannot provide this. As the Thistle may be shaped like a wind turbine, it can also be used as a windmill. As explained in [4], during high velocity wind storms a conceptual Thistle could be anchored on ground from its axis and the motors would generate energy as the wind rotates the turbine-like outer shell. Energy collection with miniature turbines from gas expansion inside the Thistle is mechanically quite simple and straightforward. The case is the simplest if Martian air can be used as an expanding agent and gas flow happens in and out from the ball. However, the thin atmosphere of Mars makes the energy content of the expanded gas very low. By increasing the gas pressure energy gain can be increased significantly, as shown in the table. Unfortunately increased gas pressure requires closed pressurized volumes and gas leaks may become fatal or at least reduce efficiency.

RUSSIAN THISTLE PROTOTYPE

It is desirable to demonstrate locomotion capability of the robot with a simplified prototype. Since the JPL Tumbleweed represents an advanced model of a wind-propelled device, we wish to study functionality of ballast drive in this large scale (having already a lot of experience in small-scale robots). We set our primary interest on ballast drive and therefore we do not pay very much attention on mass properties or aerodynamic properties of the ball structure, although we hope to demonstrate some locomotion capability also by wind propulsion. A most simple mechanical construction of the ball was realized with 18 pieces of 2 m long 8 mm glass fiber rods, plastic poles and a connecting aluminum shaft, as shown in Figs. 8. and 9. Each of the rods forms an arc that is equipped with a sail made of nylon fabric. A ballast drive will be mounted on the aluminum axle. Considering the strength only nine pieces of glass fiber rods would have been enough, but in order to provide better rolling capabilities the number was increased to eighteen. In future even better rolling can be achieved with additional rings running orthogonal to these rods. As the Thistle has an open structure its wind drag is expected to be smaller than that for a closed ball. The open structure, however, provides better view and access to mechanisms inside. In later phases, if so desired, the interior can be closed with an inflatable ball. The ball and sails alone weight 4.5 kilograms, but significant mass savings can be achieved by using advanced materials like carbon fiber rods and axle and mylar sails.

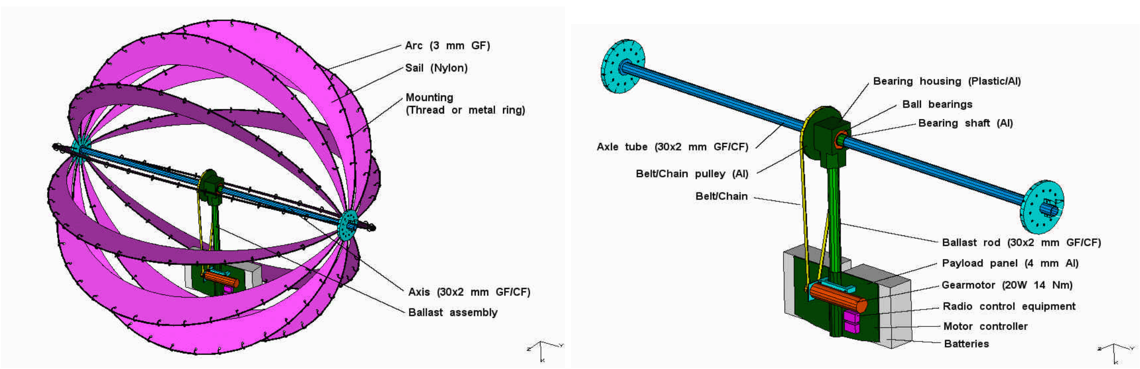

Fig. 8, Conceptual design a of the Russian Thistle prototype.

Fig. 9, The Russian Thistle prototype still without the ballast drive.

Without additional equipment and mass, assuming low drag coefficient 0.25, a terrestrial 5 m/s wind is supposed to propel the prototype over obstacles 10 cm high. Since constructed from separate arcs actual polygonal shape of the Thistle equals to 1 cm obstacle height. So in order to roll over smooth surface the Thistle would require a 2.7 m/s wind. With additional 5.1 kg ballast mass we expect the prototype to roll over 10 cm obstacles, while wind propulsion would then require 7.3 m/s velocity to overcome similar obstacles or 3.9 m/s on smooth surface. Bending of the arcs will, however, somewhat decrease rolling performance of the prototype.

CONCLUSION

This work has studied locomotion and energy production on Martian surface over a very large range of technologies. It has been shown that it can be useful to combine direct wind propulsion and ballast drive to produce an efficient ball-shaped moving robot for Mars. The final conclusion and system proposal is in large extent a conceptual and preliminary one. Locomotion capability calculations presented 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 conceptual model or as a proof-of-principle.

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