SHRIMP: A ROVER ARCHITECTURE FOR LONG RANGE MARTIAN MISSION

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ABSTRACT

Long-range robotic missions for Martian exploration imply a high degree of autonomy. As a matter of fact, human teleoperation from Earth reduce the mission range due to the transmission delay and cannot be considered anymore. Moreover, the low solar radiance combined with the dusty atmosphere allow only low power consumption and the extreme temperature encountered reduce drastically the energy storage capabilities. New locomotion concepts have to be developed and investigated allowing to increase mobility and subsequently reduce calculation and power consumption. In this case, autonomous robots with virtually no power storage ability can be considered.

The most advanced locomotion concepts are based on wheels or caterpillars (e.g. Sojourner, NASA or Nanokhod, ESA). These rovers have clear advantages regarding power efficiency and complexity if compared with walking robots. However, they still have quite limited climbing abilities. Typically they can only overcome obstacle smaller than their wheel size.

In this paper we present Shrimp, an innovative long-range rover architecture with 6 motorized wheels. Using a rhombus configuration, the rover has a steering wheel in both, the front and the rear, and two wheels arranged on a bogie on each side. The front wheel has a spring suspension to guarantee optimal ground contact of all wheels at any time. The steering of the rover is realized by synchronizing the steering of the front and rear wheel and the speed difference of the bogie wheels. This allows for high precision maneuvers and even turning on the spot with minimum slip.

The use of parallel articulations for the front wheel and the bogies enables to set a virtual center of rotation at the level of the wheel axis while maintaining a high ground clearance. This insures maximum stability and climbing abilities even for relatively low friction coefficients between the wheel and the ground. This rover is able to passively overcome unstructured obstacles of up to two times its wheel diameter. With this high mobility, this architecture is the perfect candidate for long range planetary missions.

A well functioning prototype of 3.5 kg has been designed and manufactured. A demonstration in the Mars surface testbed of ESTEC will be done during the conference.

Keywords : locomotion, roving vehicles, planetary rover, Mars exploration

INTRODUCTION

NEW MISSION OPPORTUNITIES ON MARS

Performing research at locations very distant from the landing location (hundreds to thousands of kilometers) climbing up mountains, volcanoes (e.g. Olympus Mons 24 km high) or down valleys or craters (e.g. Valles Marineris 6 km deep, 4000 km long), constitute abilities that offer new mission opportunities because these places might reveal much more geological and exobiological information than everywhere else on Mars.

Such missions pose new requirements on the rover system :

- The navigation reference point cannot be a lander but has to be either an orbiter or other means.
- The long operation time requires local power generation rather than a one-time energy storage. The short term energy storage needs a long lifetime, high energy density at low temperatures.
- The integrated (solar) power generation restricts the journey to zones with sufficient energy supply (sunny side of mountains or valleys)
- Low power consumption per traveled distance determines the average speed at reduced light radiance.
- Due to the long mission duration high autonomy reduces the mission control resources.
- Low power consumption and yet high autonomy requires simple, reliable systems with a low number of consumers such as active control loops, microprocessors etc.
- For low power consumption a locomotion system using wheels is the best.
- In long range missions zones with very rough terrain cannot always be avoided. Hence, good mobility such as climbing ability and ground clearance is necessary.
- While traveling in very rough terrain tipping over cannot always be avoided. Therefore a recovery measure must be provided.
- Moreover, the low mass, the high mobility and the ability to recover after tipping over allow landing in rougher terrain than used in the past. Therefore the number of accessible research locations is even further increased.

- The low mass and dimension allows several rovers to be landed in one or more landing sites during one mission.

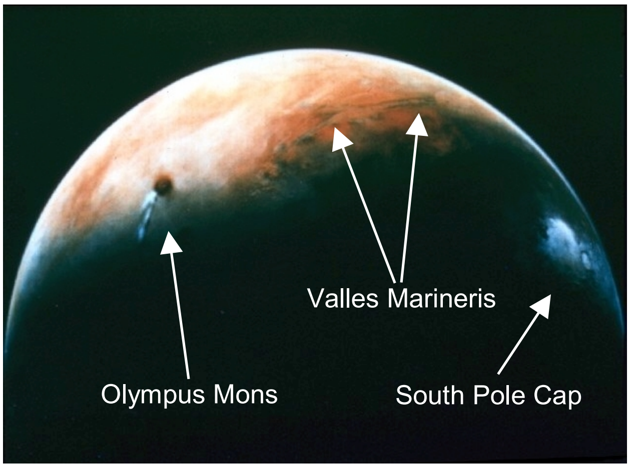

Fig. 1: Overview of interesting research sites on mars

Long-range scientific exploration should consist of an orbiter and one or several rovers with long-range capabilities. This concept facilitates communication to earth (rover → orbiter → Earth) and allows to track the rovers. Such a mission scenario also results in a more efficient use of the resources because the orbiter can be reused for a whole family of subsequent rover missions that could land in very distant areas around a planet or moon.

In absence of a lander, the landing of the rover is realized through a combination of much smaller reentry shields and parachutes with airbag cushions. However, these landing technologies have the risk that the rover might not touch down on its wheels and the landing area is hardly controllable precisely. Thus the rover has to have sufficient recovery capabilities after landing which could be integrated with the means of recovery after tipping over.

SCIENTIFIC GOAL

In analogy to the journeys of terrestrial discoverers there are three broad and partly interrelated topics:

1) Geography / topology / climate
2) Geology / mineralogy
3) Biology - in this case exobiology

According to Dr. R. Rieder, Max Planck Inst. for Geochemistry, the role of a long-range rover can be seen in this context as an important complementary research element to landers with short-range mobile robots. It enables:

a) discovering areas potentially not accessible by stationary landers because of technical constraints,
b) exploring areas further remote from, or along stretches between, stationary landers,
c) obtaining more detailed geographic and topographic information (e.g. images of higher resolution; the best images from orbiting cameras are currently limited to ca. 1.5 m per pixel. Images taken by lander- and rover-based cameras can resolve structures in the cm to mm range);
d) Item a) deserves particular attention, because currently employed landing techniques and their targeting accuracy do not permit to land in apparently very rugged terrain, in closely confined areas like craters or valleys, and in more elevated areas. Thus, two of the most fascinating structures on the surface of Mars, the Valles Marineris (a canyon system extending over some 4000 km length, whose floor lies up to 6 km below the level of the adjoining plateaus)

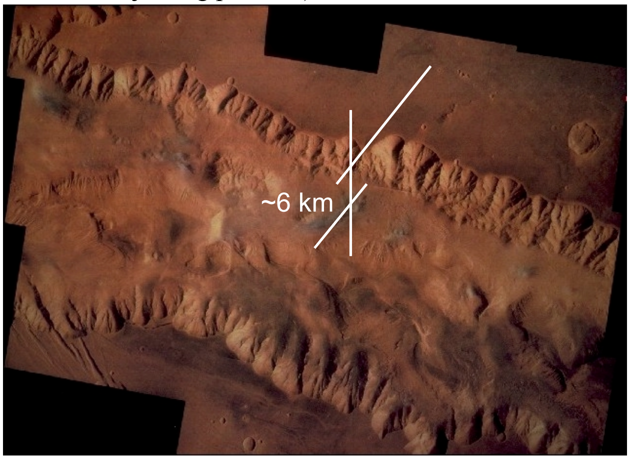

Fig. 2: Part of Valles Marineris

and the Olympus Mons (a volcano extending ca. 24 km above the surrounding lava plains and with this being the highest mountain in the Solar system) can not easily be reached with current technology landers. A long-range rover might land in a safe place in the vicinity of these structures and then attempt to drive into/onto them.

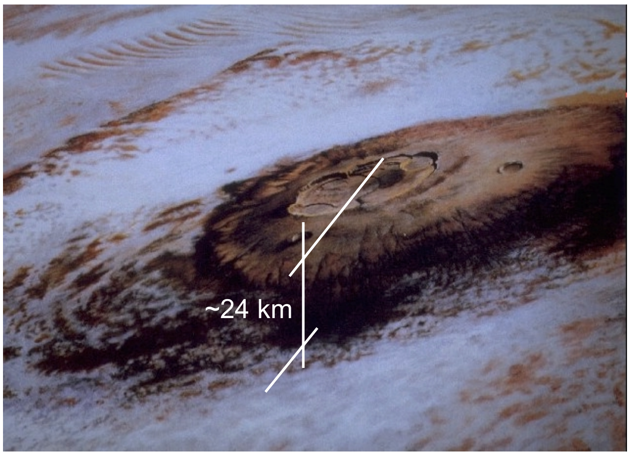

Fig. 3: Olympus Mons towering over a cloud layer

An attempt to reach the floor of Valles Marineris is of particular interest for two reasons:

1) Strata in the walls of this canyon may present in their vertical arrangement a unique record of Martian geological history, otherwise only accessibly by deep drilling - a wealth of information and the dream of every geologist.

2) If there has ever been water on Mars, and if the presence of this water has enabled the development of life, then the likelihood of any of these life forms being preserved to the present day is probably the highest somewhere in this low lying canyon, where atmospheric pressure and temperatures are still higher than average and even traces of liquid water may have been preserved in underground layers.

However, for operation in a valley the availability of solar energy must be checked.

A long-range rover, equipped with a camera for high resolution panoramic imaging and with a properly selected, highly miniaturized instrument package to address some of the key issues of geology/mineralogy and exobiology (see also NASA's Athena-2 project or ESA's exobiology initiative) would thus constitute an excellent research tool for a further refinement of our knowledge of Mars.

ENERGY HOUSEHOLD

As Shrimp will run on solar power only, the power management is of high importance.

The orbital solar intensity on Mars is only ~43% of that on Earth because of its bigger distance to the Sun. The average solar intensity in the orbit of Mars is in the order of 600 W/m2. The intensity on Mars's surface is then further reduced to 50% of this value on a clear day or even to 20-30% on cloudy days. Additionally it also depends on the meridian of the actual rover position.

		Red. Factor	Worst Case	Best Case
Solar Constant (Distance to sun)	W/m2		485	705
Clear Athmosphere Transparence	%	50%		353
Cloudy Athmosphere Transparence	%	30%		
Global Storm Transparence	%	15%	73	
Solar Cell Area	m/2	0.2	15	71
Solar Cell Efficiency, new, clean	%	15%		10.6
Solar Cell Efficiency, degraded	%	10%	1.5	
average Noon Sun Angle wh.driving	deg	70	**1.4**	**9.9**

Table 1: available Power on Mars [LAN91]

Figure 4 represents a typical solar intensity distribution during a Martian day (24h37').

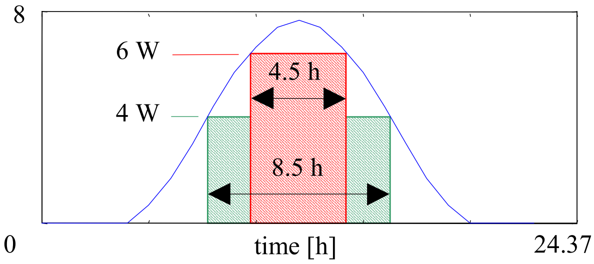

Fig. 4: Solar power on SHRIMP [array 0.2 m2]

If we assume a maximum efficiency of the solar cells including the power converter of 15% we can calculate the solar power generation of the 0.2 m^2 solar array of SHRIMP (fig. 11). Presuming a power consumption of 6 W for full speed movement, the rover will be able to operate during a period of 4.5 hours. During cloudy days or at a meridian fare from equator, this operation time might be drastically reduced. Furthermore, as experiments during the Pathfinder mission have shown [LAN97], dust deposition on the solar array might reduce the power with a rate of 0.3% per day. To avoid this deterioration the solar array will be equipped with a cleaning system e.g as a special function of the manipulator arm. The inclination angle of the solar array has also an important influence on the available solar power. However, it might anyway be advisable to reduce the speed of the robot during climbing operations. Additional mountain climbing has to be planned in such a way that the solar array get most energy.

Mars Power Budget	**Operational Mode**		
	Locomotion	**Measurements**	**Communication**
Actuators	4 W	1 W	
Controller	1 W	1 W	1 W
Navigation Sensors	1 W	-	
Communication	-	-	3 W
Scientific Instruments APX (one sensor MOS at a time) CUI Additional sensor	-	1.5 W (1.5 W) (1 W) (2 W)	-
Total consumption	6 W	< 4 W	4 W
Max. Solar power, peak hours (4.5h) side hours (2x2h)	~6 W ~4 W	~6 W ~4 W	~6 W ~4 W
Margin during peak hours (4.5h) during side hours (2x2h)	0 W -	2 W 0 W	2 W 0 W

Table 2: Power budget of SHRIMP

As can be seen from the power budget table, there is little power margin in locomotion mode. Fast locomotion is thus only possible during peak hours on non-cloudy days. It is therefore unavoidable to focus on this point during the project to optimize the power consumption during locomotion mode.

LOW TEMPERATURE ENERGY STORAGE

Usually with the use of solar power generation an energy storage is used for bridging passing shadows and night operation and to deliver peak power. Due to the intended challenging mission the requirements for such an energy storage are also challenging.

- Due to the necessary long lifetime *a high number of charging cycles* is required.
- The low availability of sun energy and the wish for low mass require *deep discharging* to make full use of the storage capacity.
- In order to save as much mass as possible with the thermal control system the energy storage should not be its design driver. Thus the energy storage should be operable at the *lower temperature limit* of the payload with the highest low temperature limit. e.g. the electronics at about –50°C.
- For climbing over obstacles or for recovery after tipping over discharging with *peak power* is required.

However, there are also some mission restrictions that relax the energy storage requirement:

- Due to the autonomy the rover does not need to move, process images and broadcast at the same time.
- It is not necessary to drive at night; just to survive it.
- The stored energy should be sufficient to supply the rover for some minutes with peak power and for a night length with survival power.

The most used types of energy storage are electrochemical batteries with NiCd or Li-Ions. However, depending on chemical reactions these batteries are temperature sensitive which limits the low temperature capacity and peak power. Since the chemical reactions are not completely reversible the number of charging cycles is comparatively low. However, the energy density is very good.

As an alternative solution double layer capacitors typically use high surface carbon and sulfuric acid as electrolyte and utilise the physical principle of moving electric charges. This in itself is not directly temperature dependent, but the motion of charges in a cold or frozen electrolyte does affect and limit the performance. However, the operation is possible at considerably lower temperatures than batteries. The fully reversible physical effect allows very high cycle numbers and very high charging and discharging peaks. On the other hand, the energy density is only in the order of lead batteries.

As a second alternative there are mechanical energy storage such as springs or fly wheels. They can be made appropriate in terms of charging cycles, peak power and low temperature operation. However the energy density would be very low and therefore either its mass very high or the available capacity very low.

Sojourner used one-way Lithium-Thionyl Chloride (Li-SOCl2) batteries with an energy density of ~500Wh/kg. There are now Li-Ion cells for space application with about 120 Wh/kg and double layer caps have about 2-3 Wh/kg all at room temperature. A trade-off has to show the best compromise between lowest operating temperature, useful capacity at low temperatures and deep discharge limitation and lifecycles compared to the mass of the thermal protection system defining the lower operating temperature.

MECHANICAL DESIGN

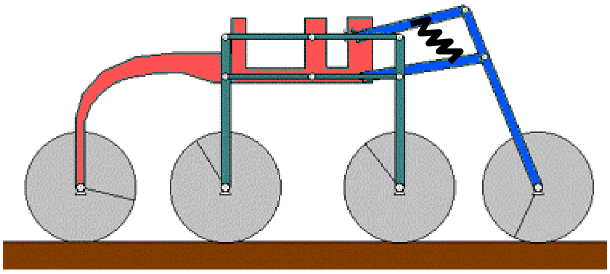

Fig 5: Schema of the mechanical architecture

OVERVIEW

Using a rhombus configuration, the rover has one wheel mounted on a fork in the front, one wheel in the rear and two bogies on each side. Although our bogies have a special geometry, it is the same basic principle as used for a train suspension : a couple of two wheels mounted on a support which can freely rotate around a central pivot.

The front fork has two roles : its spring suspension guarantees optimal ground contact of all wheels at any time and its particular parallel mechanism produce an elevation of the front wheel if an obstacle is encountered (fig. 6).

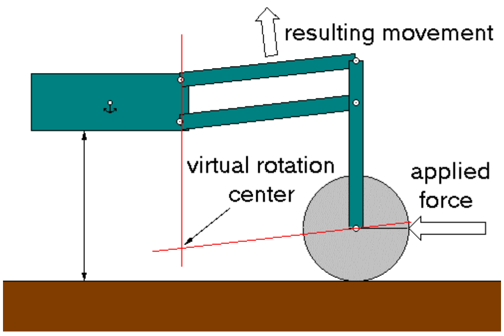

Fig 6: Working principle of the front fork

The parallel architecture of the bogies and the spring suspended fork provides a non-hyperstatic configuration for the 6 motorized wheels while maintaining a high ground clearance. This insures maximum stability and adaptability as well as excellent climbing abilities.

The steering system (explained later in this article) allows the rover to carry out a pure rotation even in these extreme situations.

BOGIES

The bogies are the first key components of the rover. They provide the lateral stability during the motion even on very rough terrain. To insure good adaptability of the bogie, it is necessary to set the pivot as low as possible and in the same time to keep a maximum ground clearance. This problem is solved by using the parallel configuration showed on fig. 7 that bring the virtual center of rotation of the bogie at the height of the wheel axis.

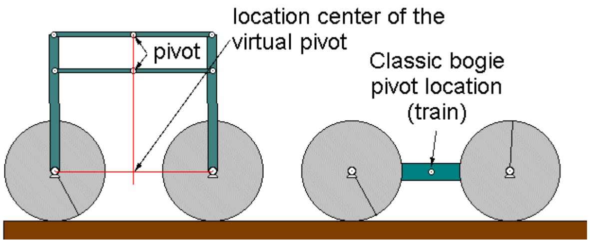

Fig 7: Explanation of the parallel bogie architecture

FRONT FORK

As shown on Fig. 6, a trajectory of the front wheel with an instantaneous center of rotation situated under the wheel axis is helpful to get on an obstacle. The second goal for the fork is to provide a maximum vertical amplitude for the wheel. To find the optimal configuration for the fork, we established the following kinematic model (fig. 8) :

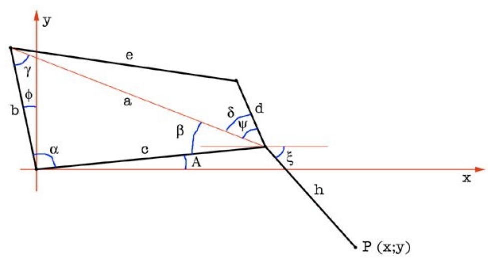

Fig 8: Parametric model of the fork

With the parametric equations of ξ, α et ψ as function of the angle A,

$$\alpha(A) = \frac{\pi}{2} - A + \phi$$

$$\psi(A) = a\cos\left[\frac{c - b\cdot\cos[\alpha(A)]}{\sqrt{b^2 + c^2 - 2\cdot b\cdot c\cdot\cos[\alpha(A)]}}\right] + a\cos\left[\frac{b^2 + c^2 - 2\cdot b\cdot c\cdot\cos[\alpha(A)] + d^2 - e^2}{2\cdot d\cdot\sqrt{b^2 + c^2 - 2\cdot b\cdot c\cdot\cos[\alpha(A)]}}\right]$$

$$\xi(A) = A - \psi(A)$$

we have all elements to establish the position of the point P as function of the angle A:

$$P(A) = \begin{pmatrix} c\cdot\cos(A) + h\cdot\cos[\xi(A)] \\ c\cdot\sin(A) + h\cdot\sin[\xi(A)] \end{pmatrix}$$

Finally, we chose the different parameters to get the trajectory shown on fig. 9. The horizontal line is the height of the wheel axis when the robot is on a horizontal plane. Note that the characteristic of the trajectory under this line is needed to insure a good stability when the rover is on a convex ground.

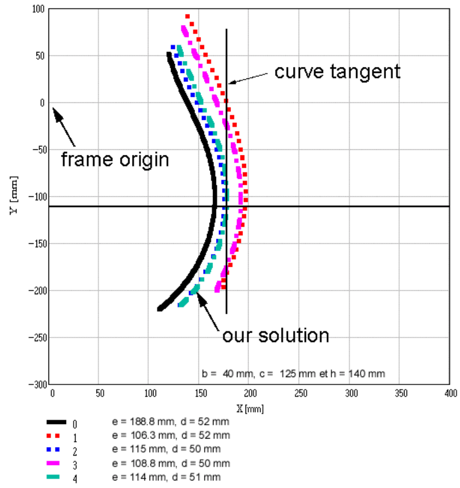

Fig 9: Trajectories of the wheel axis of the front fork

STEERING

The steering of the rover is realized by synchronizing the steering of the front and rear wheels and the speed difference of the bogie wheels. This allows for high precision maneuvers and even turning on the spot with minimum slip.

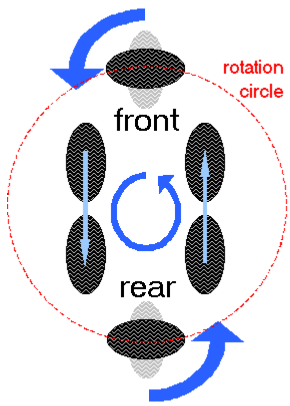

Fig 10: Configuration of the wheels on ground

With two motors less than the K9 (or Sojourner) architecture, this configuration allows to follow curved trajectories in motion, therefore increasing the mobility of the robot and its ability to keep its stability in critical situations.

As function of an angle of gyration *alpha* and an overall speed *Vref*, three distinct speeds must be assigned: *V* for the front/back wheels, *Vext* for the wheels of the external bogie and *Vint* for the internal bogie.

As it can be seen on Table 3, this can be easily implemented on very simple micro-controllers defining *V*, *Vext* and *Vint* as ratio of *Vref*. Using only relative speeds of *n/8*Vref*, it can be done only with byte shifts and byte additions, which are the most basic instructions of processors. That means that even with different speeds for each wheels, it can be done consuming little calculation power.

alpha	Vext	V	Vint
0	1	1	1
10	1	7/8	6/8
20	1	7/8	5/8
30	1	7/8	4/8
40	1	7/8	2/8
50	1	7/8	1/8
60	1	1	-0
70	7/8	1	- 2/8
80	6/8	1	- 4/8
90	5/8	1	- 5/8

Table 3: Simple implementation of different wheel speeds as function of the steering angle

RECOVERY STRATEGY FROM TIPPING OVER

Due to the extremely challenging terrain in which the robot will move about, the risk of falling and tipping over can't be ignored and a recovery strategy has to be established.

An interesting solution lies in the use of the robotic arm which has been designed especially for this robot with the following guidelines:

- Low position of the center of gravity and low inertia, even in fully deployed configuration.
- Ability to position tools (micro-camera, micro-spectrometer, drill, etc.) around objects of interest at the ground level.
- Ability to mechanically clean the whole surface of the solar panels.
- Ability to move a panoramic-camera in high position for reconnaissance purposes
- Possibility to recover the robot after a tipping over.

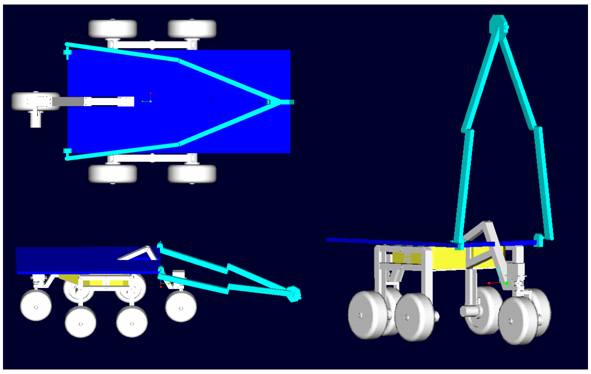

Fig 11: Various configuration of the robotic arm.

This arm is based on a parallel structure actuated at the level of the solar panels (except for the rotating joint at the end of the arms). This allow to provide an excellent workspace volume for the tools and even to reach the ground with the elbow of the arms to put the robot on its wheels after a fall (shown figure 12).

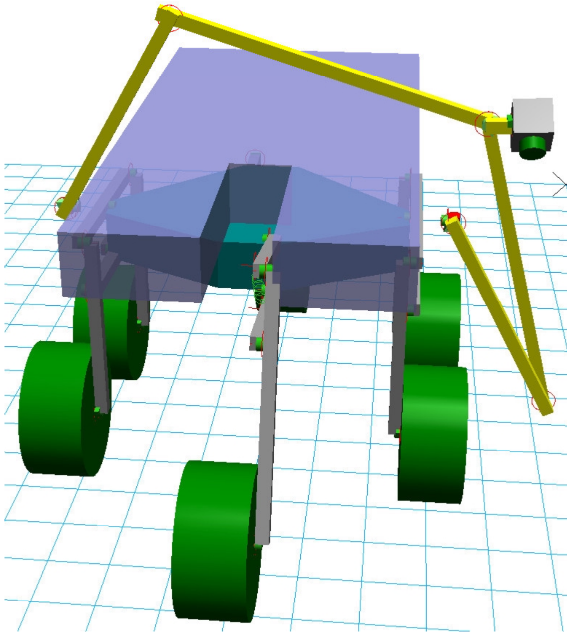

Fig 12: Dynamic simulation results of the shrimp arm helping the robot to recover

EXPERIMENTAL RESULTS

This section presents some of the tests we performed with our first prototype manufactured at EPFL.

OVERCOMING ABILITIES

To evaluate the getting over abilities, we performed several test on a critical configuration: the overcoming of a vertical step. Fig. 13 shows the main sequences of the rover climbing a step. First, the front fork gets on the step, compressing its spring (shown fig. 6), then the energy accumulated in the spring helps the first wheel of the bogie to climb. When the second bogie wheel is in contact with the wall, the bogie turns around the step. At this time the center of gravity reached almost its final height. Finally, the last wheel can easily get on the step.

Fig 13 Climbing sequence for a step of 22cm high (twice the wheel diameter)

As the two bogies are independent from each other, it is even possible to climb the step if the robot is not approaching perpendicularly or if only one bogie encounters a step. Although it was designed to climb steps up to 17 cm, the rover is able to climb even steps of twice its wheel diameter (22 cm).

The climbing ability is mostly given by the sequential rising of the center of gravity (CoG) provided by the consecutive action of the wheels. Figure 14 shows the trajectory of CoG for a step climbing of 17 cm. The center of gravity goes up to 10% of the final height when the front wheel is on the top of the step (fig 12b). Then the first bogie wheel, helped by the action of the front fork, brings the CoG to 50%. The second bogie wheel and the rear wheel contribute each for approximately 25%. It can be seen that the mechanical structure allows a smooth movement of the CoG.

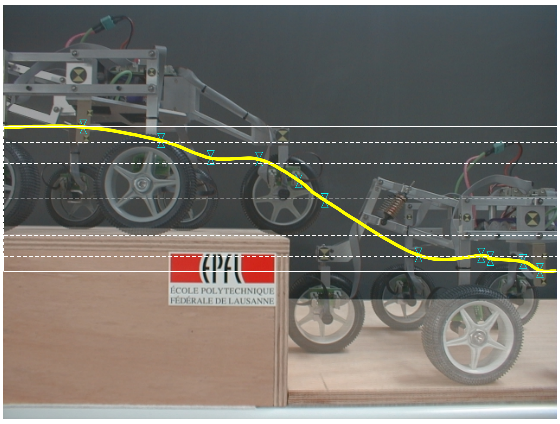

Fig 14: Trajectory of the gravity center.

OFF-ROAD ABILITIES

The rover demonstrates excellent stability in both smooth and rough terrain. It still moves with a lateral or frontal inclination of 40° (Fig 15, above) and is able to overcome obstacles like rocks even with a single bogie (fig.15, bellow). The rover was tested in various terrains (sandy and gravelly soil) and showed that its architecture was well adapted for fields motion even in dunes or in furrows.

Fig 15: Off-road stability test

Using the models described in [WIL97], we computed the Mean Free Path (MFP) for the two Viking landing sites (VL1 and VL2). We set the height of passively climbable obstacles to 17 cm instead of the true value of twice its wheel diameter because there is at this time no heavy payload on the rover. For VL1, we obtained a value of 35.7 (Sojourner: 9.6). For VL2, the MFP is 5.4 (Sojourner: 2.4). This is a clue to say that this rover architecture is an excellent candidate for long range missions.

CONCLUSION

The presented concept demonstrator proves the feasibility of the locomotion concept using wheels for low power consumption and yet achieving remarkable rough terrain mobility. This is the basis for long range missions to remote research sites even in very challenging environments with important slope and considerable number of obstacles. On Mars, it offers new scientific opportunities to reach places which are rich in geological and exobiological information.

The most crucial subsystems for this long range rover are the power train including the energy storage, the thermal subsystem, the autonomous navigation system, the recovery from tipping over, the communication system and the miniaturized payload.

In order to integrate all these subsystems successfully into a whole rover:

- a mission must be chosen,
- budgets and requirements defined and
- solution concepts for all subsystems developed.

The work for the most challenging subsystems like the thermal subsystem and the autonomous navigation system should be attacked first as they contain the most development risk. Specially for the autonomous navigation subsystem another concept demonstrator is needed for testing over long distances in rough terrain.

For autonomous systems reliability and therefore simplicity must be the most important design guideline.

Although a further development of the concept to a space proof level still requires substantial efforts, the new order of possibilities should justify it.

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