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Design of an innovative unfoldable wheel with contact surface adaptation mechanism for planetary rovers

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Abstract

In this paper, an original expandable mechanism for unfolding wheels is proposed. This mechanism combines two elementary mechanisms. One allows the deployment of the rim while the other one ensuring the contact shape adaptation. In a first section, we analyse the different deployment mechanisms already proposed in the literature. Then, the design of the rim expansion mechanism is described and two complementary version are proposed. Last, based on terramechanics model, a contact surface adaptation mechanism is proposed. This system allows to adapt the wheel-ground interaction properties and make the wheel ables to improve its traction and steering performance on soft soil.

1 Introduction

Mars exploration programs that require surface mobility, such as geology studies, search for past life or infrastructure deployment for future manned missions, make use of wheeled rovers. The total mass of the rover and its volume during launching phase are very constrained, thus resulting in moderate ability to overcome obstacles, despite the efforts in optimizing the kinematics design, due to the limitations on wheel diameter. Meanwhile, the wheel size is one (but not the only) important parameter that determines the rover crossing performances. These limitations can be reduced by introducing mobilities in the system for the deployment of the locomotion mechanism from a stowed configuration or/and using inflating or unfolding wheels that can reach large diameters and thus present high cross-country ability, still being compatible with the launching constraints. The adaptation of the contact surface geometry of the wheels is another important feature which will allow to optimize traction and mobility performances of non-holonomic vehicles with respect to the physical characteristics of the ground. One of the purpose of the INTAS Project untitled Innovative Mars exploration rover using inflatable or unfolding wheels is to study mechanically deployable wheels and compare them with classical rover wheel design, given the same mission objectives and constraints.

Many sorts of deployable structures exist, based on a variety of different concepts. Some of these structures form planar or space frames and have already had a variety of applications [7] [4] : space applications for solar arrays, solar sails, etc or architecture applications to support membranes or films. The most impressive example of these deployable structures, certainly within the field of architecture are retractable roofs. The paper describes a new type of expandable mechanisms with 2 degrees of freedom (dof). This mechanisms combines 2 elementary mechanisms which allows the deployment of the rime the other one ensuring the modification of the rolling tread geometry. To obtain this expandable mechanisms, planar linkages with 1-dof have been design and optimized in their kinematics to obtain the desired expansion ratio for the former one and its rigidity under a radial load for the other one. These planar units are then assembled to form the desired "solid".

2 Deployable mechanisms

Reversible foldable mechanisms are such that their structure remains stress free throughout the deployment. They are capable of expanding from a closed, compact configuration to a pre-determined form while modifying their dynamics. They can be classified as follow:

1. structures with rigid 1-D bars connected to each other in various 2-D or 3-D pantographic arrangements;
2. structures with 2-D panels connected to form various surface structures, basic element being a triangular panel[6];
3. tension structures consisting of cables or membranes, or combination of both, either pre-stressed or pneumatic[4];
4. deployable tensegrity structures composed of rigid rods and cables[10, 1];

The two last one combined are said active-form systems since they allow to create a structure that could autonomously adapt its shape and mechanical behavior with its environment. This idea will be reused for the design of the "casing of the tire" in the deployable wheels proposed in this paper. Several bar mechanisms have been invented to create reversible foldable structures along its external perimeter or surface. Most of them are made of hinges and pivots and are able to move in a plane, along a cylinder or sphere.

Emilio Pinero pioneered the use of scissor mechanisms to make deployable structures. Scissor hinge structures are built out of basic units composed of rod elements connected in there center and with each other by hinges. The basic unit (a Scissor-Like Element) is a pantograph. These units can be assembled to form an opened or a closed loop system with a single degree-of-freedom. Fig.1 consider different planar arrangements of parallel straight or angulated rods.

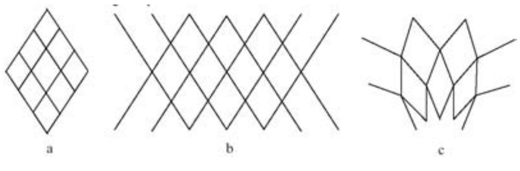
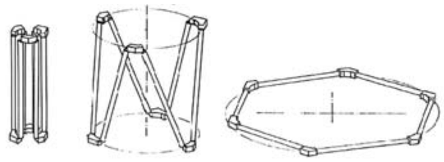


Fig. 1: Multiple scissor-like elements with straight rods or angulated rods

Space frames can be formed by closed loops of these elements. Fig.2(a) shows an example of a mechanism which was adopted in th edge beam of the Hoop-Column Antenna [5] and built with half-scissor mechanisms. This kind of structure must have an even number of equal-length hinged segments with a rotational joint at each extremity whose axis is orthogonal to the segment. Here, the joints of 2 consecutive segments are not collinear but form an angle in the plane perpendicular to the symmetry axis of the structure. It can be checked that due to its particular geometric properties, the mobility of this mechanism is equal to 1.



(a) Half-scissor closed-loop deployable mechanism [5]

(b) Expanding "4-gon" and "6-gon" based on Hoberman design (from [9])

Fig. 2: Closed-loop deployable mechanisms

Hoberman has also created numbers of pantograph mechanisms that operate in two and three dimensions. A "N-gon" as shown in Fig.2(b) can expand out in a symmetric manner by "actuating" only one of its members [9]. When scissors-pairs are connected in closed-loop via angulated elements in such way that the normal line that are perpendicular to the axis of the joined terminal pivot of adjacent scissors-pair intersect, a reversible folding of the structure take place without internal constraints in the structure [7].

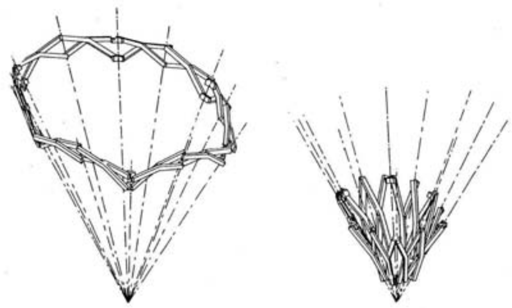


Fig. 3: Configuration where the pivot points of all the scissor-pair lie on a circle

3 Wheel expansion mechanism design

One important property of an expandable wheel is the expansion coefficient which is basically defined as the ratio between the wheel diameter in expanded configuration and the one in compact form. The expansion coefficient λ is the metric describing the deployment capacity of the wheel. It is defined as the ratio of the characteristic length (here the wheel diameter D) between the compact and the unfolding configuration :

$$\lambda = D_{\max}/D_{\min}$$

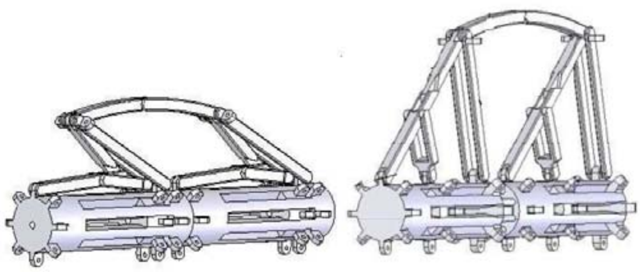
The second point is the ability of the wheel to adapt both the tread geometry and its elastic mechanical properties and so the compliant behavior of the complete wheel. Thus, the mechanisms which had been design for creating a deployable wheel can be decomposed in 2 subsystems:

- a mechanism for the radial expansion of the rim of the wheel,
- a mechanism for deformation of the contact surface geometry.

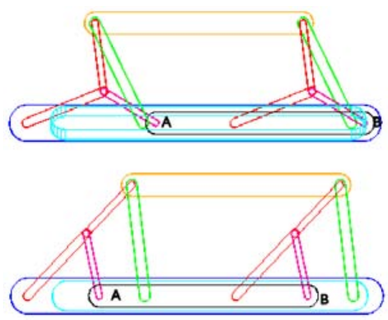
In this paper, a previous designed wheel is briefly presented and then a new mechanism is proposed which improve the total expansion coefficient. The second concept was optimized through a parametric analysis of rod dimension parameters.

3.1 Preliminary concept

The first concept[3] was initially proposed in the aim to have shape for the wheel similar to the one of the Marshokod robot [8]. The expansion of the rim is based on the use of a set of identical planar mechanisms disposed radially which play the role of spokes. Each of these mechanism can be seen as a parallel mechanism whose limbs are imbricated 4-bars mechanisms (see Fig.4).



(a) CAD view of the rim sector



(b) Schematic view

Fig. 4: Mechanism used for the expansion of the rim

The inputs are the linear motions of points A and B which are coupled to the same linear actuator placed in the hub of the wheel. When these "spokes" are totally deployed, the mechanism is in a stationary configuration. This local singularity happens when the coupling bar is parallel to the upper bar of the 4-bars mechanism. Therefore, the mechanism becomes an immovable structure regardless of the input. Moreover, in this configuration the actuator does not work in any external force applied on the upper 4-bars mechanism.

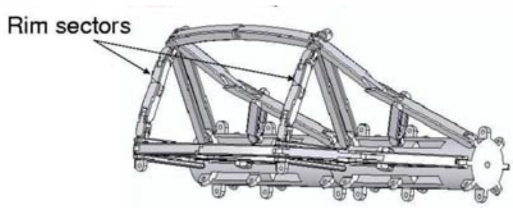


Fig. 5: Rim sector deployment system

The rim itself is a loop-assembly of rigid 2-bars (a rim sector) joining consecutive spokes, each rim sector being articulated on a spoke by a universal joint. Fig.6 shows the deployment of a rim sector simultaneously to the deployment of the spokes.

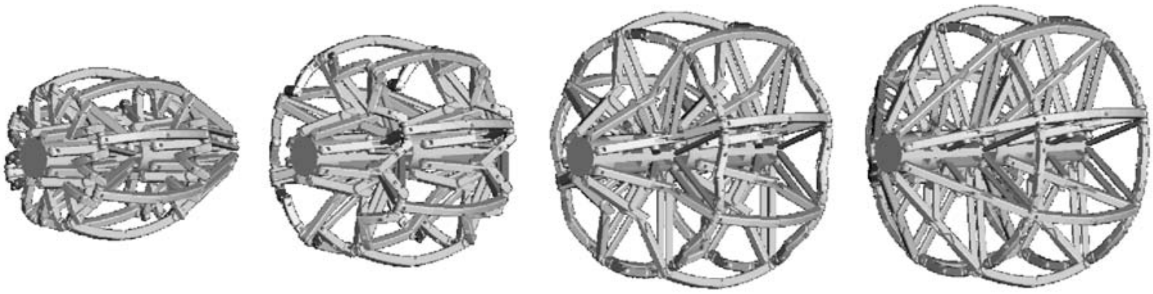


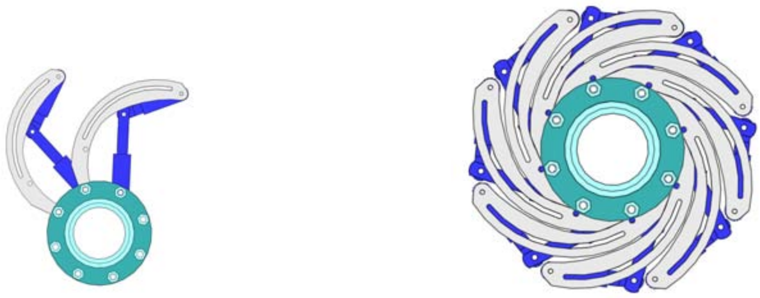
Fig. 6: Preliminary concept : folding/unfolding process.

The expansion coefficient of this first mechanism concept is about $\lambda = 1.3$. This system notably offers : a good expansion ratio, a strongly rigid mechanism with 4-bar parallel system and a stable unfolding situation by using a singular configuration of the mechanism. But, from the technical point of view, this concept is complex in its manufacture. This mechanism intensively makes use of small parts and it presents some difficulties for its assembly. Furthermore, in this design the general shape of the wheel is constrained to have a width larger than the radius because of the special expansion kinematic. This characteristic can be inconvenient in certain context of application. So, we propose a new design which is very different in its kinematic design.

3.2 New design

The second concept use an expansion mechanism which is actuated by a rotation of each lateral rim part. Each part are composed of arc-shaped rods which are in contact in the compact form. In this concept, the expansion of the wheel is obtained by a motion of elementary rods constrained in the sagittal plan whereas it was in a perpendicular plan for the first concept. This property is interesting because the ratio between the wheel width and diameter is not constrained, and thus the global shape of the wheel can be freely chosen.

The expansion of the rim is based on a three-beam planar mechanism. This mechanism shown in Fig.7 is the elementary mesh that constitute one of two lateral parts of the wheel. To insure a very compact closed form, arc-shaped rod have been used and optimized in shape as shown in Fig.7. The length ratio between the beam had been optimized to offer the most compact configuration and the best distribution of forces (rigidity). The main problem was to solve the collisions between each parts of the mechanism that were the most important constraints. We use a standard optimization method of minimization problem under algebraic constraints. The criteria to minimize was the inverse of expansion ratio $1/\lambda$. The obtained solution was then partially modified in order to integrated other technological constraints such as the need of ball-bearing parts in articulations.



(a) (b)

Fig. 7: Kinematic schema of the radial expansion mechanism

The wheel is then composed of two of these radial expansion mechanisms arranged laterally. They are coupled by a common actuation system and also connected together with the tread parts. The Fig.8 shows the whole mechanism during its deployment motion. This second design is interesting as its expansion ratio which is about $\lambda = 1.8$ is much more important. Furthermore, it offers the characteristic to be adapted to different wheel shapes as the ratio between its width and its diameter is not constrained by the kinematic. As the previous design, it also use a singular configuration to stay in unfolded situation. Unfortunately, this concept will be less rigid than the previous one. But, this characteristic can be integrated in order to confer to the wheel a useful global compliant behavior similar to the one of an inflated tire.

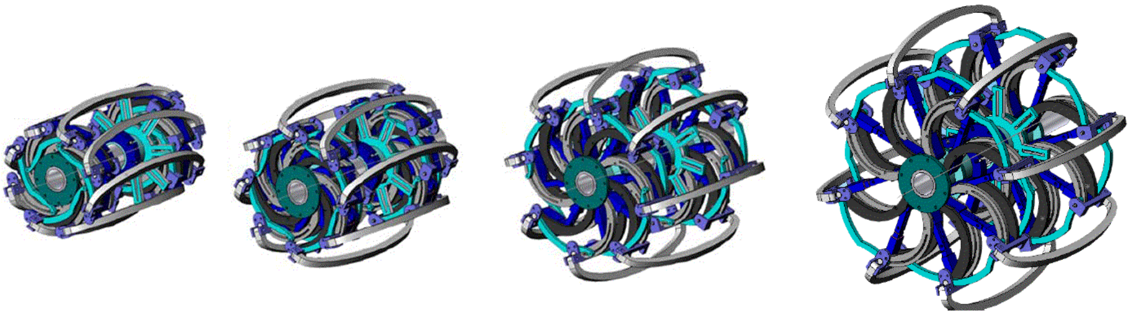


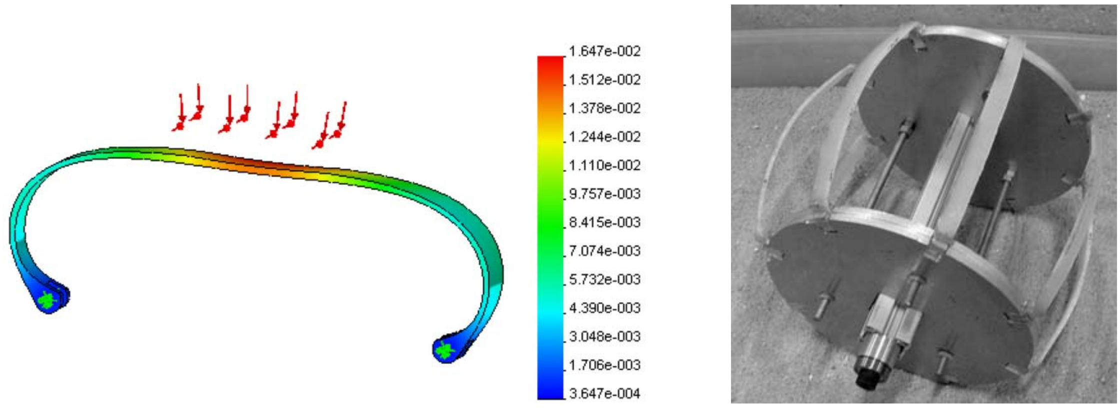
Fig. 8: New concept : folding/unfolding process.

4 Contact surface adaptation system

The dynamics behavior of mobile robot during its motion on outdoor terrain is strongly influenced by the nature of wheel ground interaction. The wheel ground contacts are the kinematic joint that involve kinematic closed-loop in the mechanism. Thus, the global performance (traction, stability,...) of a planetary rover evolving on natural soil can be improved if the behavior of the wheels-ground contact can be adapted to the variation of soil geometrical and physical properties.

In the case of mechanically unfoldable wheel when it is exposed to a vertical load and a traction force, the carcass will deform. This deformation is mainly due to the flexible rods that constitute the wheel tread. A precise estimation of its deformation has be performed using a finite element linear analysis (FEA) on an isolated radial element. This analysis have been made by using COSMOSWorks design analysis software that is fully integrated in SolidWorks (see Fig. 9(a)).

The final wheel will make use of elastic beam to constitute a discretized tread around the wheel rim. We can notice here that the wheel is composed of two lateral unfoldable rim mechanisms. These two parts are connected together by the tread elements. In order to analyse the adaptation ability of the tread, we consider the wheel in the deployed form where each lateral rim part can be simplified by a simple disc as show in Fig.9(b).



(a) (b)

Fig. 9: (a) Elastic tread adaptation mechanisms with arc-shaped beam; (b) First prototype

In this section, we analyse the interaction parameters based on Bekker model. Then we develop the mechanical principle and the model used for the design of elastic tread elements.

4.1 Terramechanics model

In quasi-static motion, the wheel ground interaction forces could be described using the Bekker theory [2, 11]. In this model, the resulting force between the wheel and the soil depends on kinematic and geometrical parameters which are the wheel slippage i and the soil compaction z.

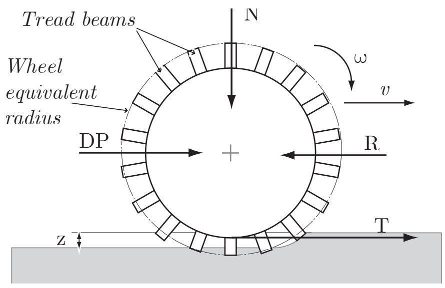


Fig. 10: Wheel ground interaction forces

The contact force under each wheel expressed in the wheel sagittal plane and decomposed in normal and tangential force. The normal force W is due to vertical load and $DP = T - R$ is the tangential force applied on the wheel where T is thrust force, R is the rolling resistance. We use classical Bekker's equations for rigid wheel to express the rolling resistance[2]:

$$R = b\left[(k_c/b + k_\phi)\frac{z^{n+1}}{n+1}\right]$$

The wheel-ground sinkage z depends on the pressure exerted on the soil and its compaction parameters. This pressure is function of the normal load applied on the wheel and its pressure for an inflated tire. In our case, the compliant behavior of the tread can then be used to compensate this rolling resistant effect. Notably, this effect is important when the wheel is steering.

The traction force exerted by the wheel on the soil involve a shear stress state that can not exceed the maximum Mohr-Coulomb shear stress ($\tau_{\max} = c + \sigma_n \tan\phi$). This value depend on the soil cohesion c, the normal pressure

σ_n and the friction angle ϕ. The shear state at any contact point is obtained with the Janosi equation : $\tau = \tau_{\max}(1 - \exp(-j/K))$ where j is the shear displacement between the wheel and the soil. Then, the total traction force is obtained by integrating the Janosi's equation along the wheel ground contact surface :

$$T = (A\,c + W\tan\phi)\Big(1 - \frac{K}{il}(1 - \exp(\frac{-il}{K}))\Big)$$

In these equations : i is the slippage ratio; $k_c, k_\phi, n, c, \phi, K$ are Bekker's ground parameters; A is the contact area and l is the contact length.

So, it is very convenient to have a low rigidity in the compliant tread to improve the traction performance. Indeed, the surface contact will be larger and the maximum wheel-soil shear ratio will be higher.

This analysis shows that the modification of tread shape and treat rigidity is an interesting way to improve the global wheel performance. A simple strategy consists to choose a more rigid configuration for steering and a more compliant one for traction. With on line adaptation and monitoring system embedded in a planetary rover, this wheel property could be very useful to improve the rover traversability.

4.2 Principle of the compliance adaptation mechanism

Schematically, the factors affecting the contact stiffness are the shape (and material) of the carcass-element and its support (the deployment mechanism). To increase the carcass deformation, an alternative design for the carcass-element using an arched beam have been explored (see Fig.9). A smooth deformation between a geometry of the carcass corresponding to a well-inflated tire and a poorly-inflated tire can be controlled by the contact-variation mechanism described above.

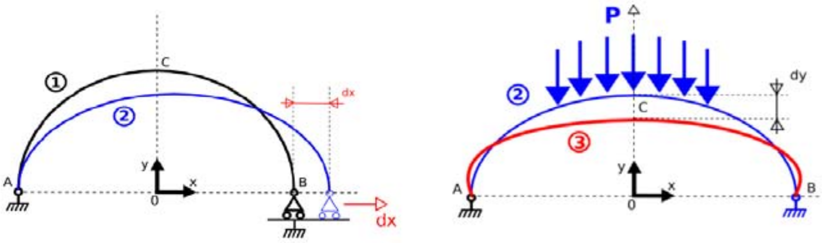


Fig. 11: Elastic deformation of a arc-shaped beam

In this configuration, the beam shape is controlled by changing the position of joint B as shown in Fig.11. Changing the shape of the beam affect is initial pre-stress state. Thus, the relation between vertical load and vertical deformation in the center of the beam is modified.

Finite element analysis shown for linear elastic material that the compliant behavior of such a single beam is also linear (it is a relation similar to the elastic spring) :

$$dy = \frac{1}{k}P$$

where k is the compliance constant of the beam. This parameters is a function of the initial pre-stress state :

$$k = f(dx)$$

The FEA computation shown that this relation is almost linear and linearity coefficient depends only on material chosen and the beam section geometry.

5 Conclusion and future work

In this paper, an original mechanism designed for creating a deployable wheel with a contact shape adaptation, has been presented. As far as we know, this is the first time an unfolding wheel integrating a rolling tread adaptation mechanism is proposed. In future work, experiments will be done to characterize the global behavior of the wheel from the terra-mechanics point of view. We will evaluate the influence of the pre-stress state in the tread elements on the global traction performance and the rolling resistance. In lab facilities will be used to conduct experiments on the wheel show in Fig.9(b). We use glass-fiber composite to constitute each tread beam as shown on the prototype. The amount of change in carcass shape remains important when using glass-fiber composite materials. Its deformation under a vertical load and its dynamical properties are much more closer to a classical inflated tire.

Acknowledgments

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