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Innovative Mars exploration rover using inflatable or unfolding wheels

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INTRODUCTION

This study has been performed in the frame of the INTAS 4063 contract. The study period was May 2004 to July 2006.
The study team was composed of :
CNES VNIITransmash KIAM RAS UIIP NASB ASTRIUM Gmbh LRP LAAS

General Context

Planetary exploration missions that make use of a rover usually land in very flat areas for safety reasons and because of the low accuracy of the landing process.
To perform the scientific mission, the rover will then have to cross long distances to reach the operational sites. The feasibility of the mission thus depends on the rover ability to find a way around the obstacles along its travel. Two ways exist to increase the daily cruising distance: giving perception and autonomous path finding capacity to the rover in order to find the best path compatible with the rover climbing capabilities on one side and increasing its cross-country ability to lower the obstacles density on the other. The first approach has been studied for a long time and is now available as operational software. The second one has been studied and the corresponding kinematics architectures optimized only for conventional wheels.

Objectives of the Research

With conventional wheels, the size is limited by the accommodation inside the fairing during launch phases, while deployable or unfolding wheels can reach higher diameters with the same accommodation constraints.
This kind of solution has been considered for Earth polar mission in the frame of the Concordia project, and is presently studied at NASA/JPL, but have never been detailed for planetary exploration in Europe. As the wheel size is one (but not the only) of important parameters that determines the rover crossing performances, it is interesting to evaluate the potential benefits of this technology.
The main scientific objective is to develop new concepts of Mars rovers with inflatable and unfolding large-diameter wheels capable to compete with conventional wheels on :

- -cross-country ability
- -maneuver-ability
- -payload-mass to lander-mass ratio
- -power budget for motion

As a result, several options of the rover system have been designed and are presented in this document. The Exomars rover baseline, as defined during phase A studies is taken as a reference for comparing the characteristics and performances.

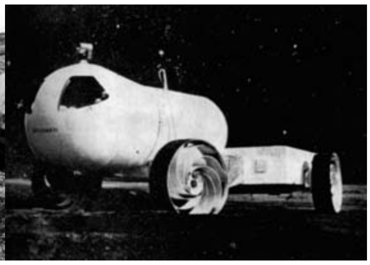
SUMMARY OF MAIN ROVER REQUIREMENTS

The leading requirements on the rover for this study were :
-the total mass of the rover shall be limited to 240 kg including 20% margin. This specification has been adapted to include part of the landing system in the rover mass, keeping the same figure for the composite lander.
-the maximum volume during launching, transfer and entry phases shall be limited as defined for Exomars phase A
-the landing shock absorption system should be designed to limit the loads on the rover to 70 g.
-the cross-country ability (steps, slopes on several soil characteristics should be, at least, the Exomars ones.

BIBLIOGRAPHY :

The first phase of the study consisted in identifying the studies and experiments on inflatable and unfolding wheels vehicles for both terrestrial and space applications. Surprisingly, many prototypes have been developed as illustrated on the pictures below :





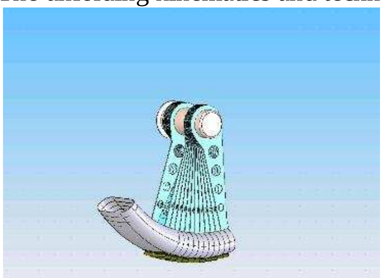
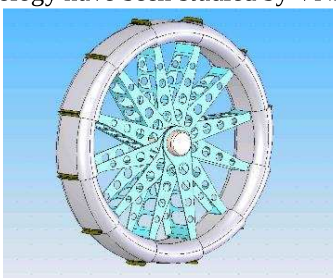



The above illustrations were collected from original projects of : Grumman Aircraft Engineering Corporation, Bendix Corporation, General Motors Company, NASA/JPL and VNII Transmash companies

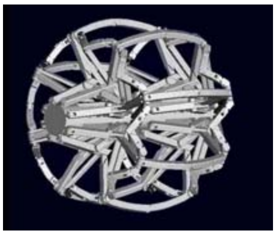
Both inflatable and unfolding wheels have been studied and several mock-ups have been developed, often guided by the necessity of increasing the traction characteristics of the wheels.

WHEEL DESIGN :

Unfolding Wheels
The unfolding kinematics and technology have been studied by VNIITransmash

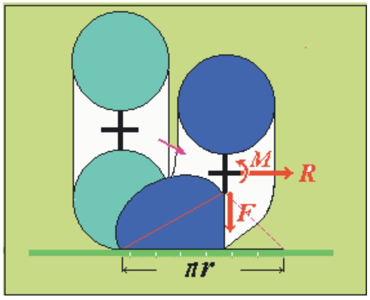
and by LRP :


Several variants of the concepts were assessed and a preliminary mass estimate was performed.
One of the main conclusions on the unfolding wheels is that it is difficult to reach very high ratios between the stowed volume and the deployed one.. This limits the diameter of the wheel that can be achieved with unfolding wheels. The mass evaluation performed by VNIITransmash on their concept also showed that the mass budget was less favourable than for inflatable wheels.
In the second part of the study, LRP continued to investigate unfolding techniques while the other teams were focusing on system design with inflatable wheels. LRP research results are presented in a poster session of ASTRA 06.

Inflatable Wheels

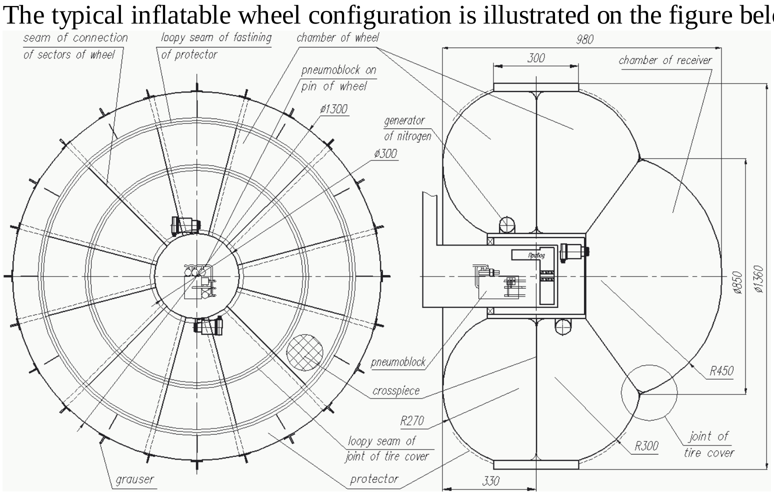
The first design of a large wheel was analysed and simulations showed a possible lateral instability of the rover as depicted in the following scheme :



The design of the wheel was thus changed to a 3 chambers one to simultaneously :

- obtain a good lateral stiffness
- have a relatively high pressure volume used for gas storage
- offer a lateral protection that will allow to use the wheels for shock protection in the landing phases.

The typical inflatable wheel configuration is illustrated on the figure below :

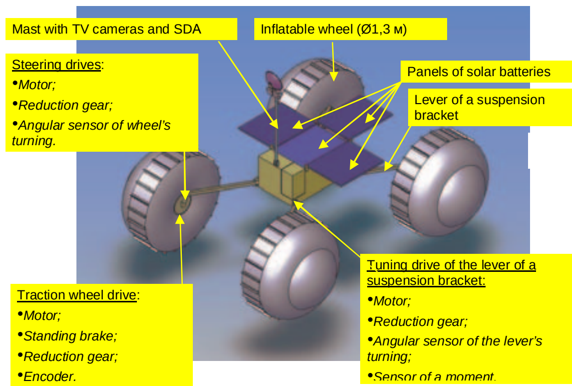


ROVER CONFIGURATIONS :

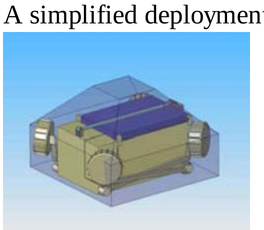
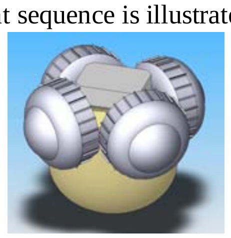
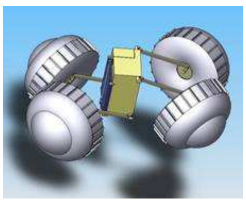
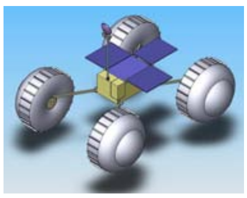
3 different configurations were studied and compared . The Pasteur scientific instruments package as well as the drill was implemented on the rovers and the operational constraints induced were acknowledged.

Concept 1

The first one has a single rigid body and use an additional airbag to damp the first landing shock, while the wheels act as protections for secondary impacts.

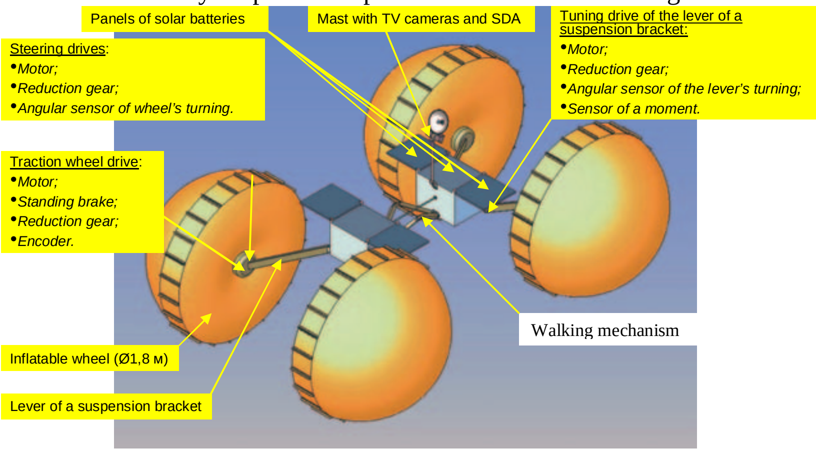


A simplified deployment sequence is illustrated below :

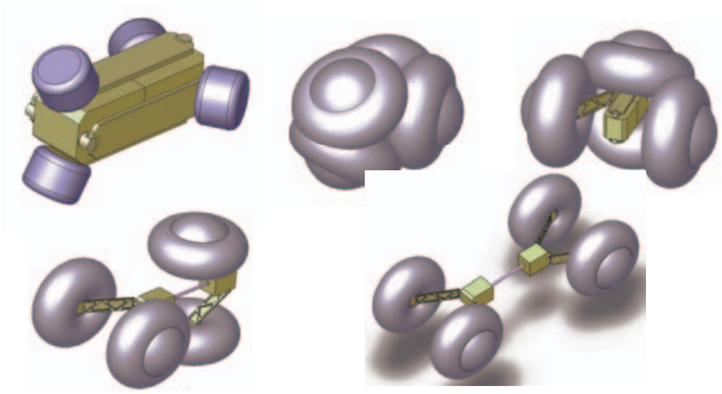
Concept 2

On the second configuration the main body is split into 2 parts connected via a walking mechanism

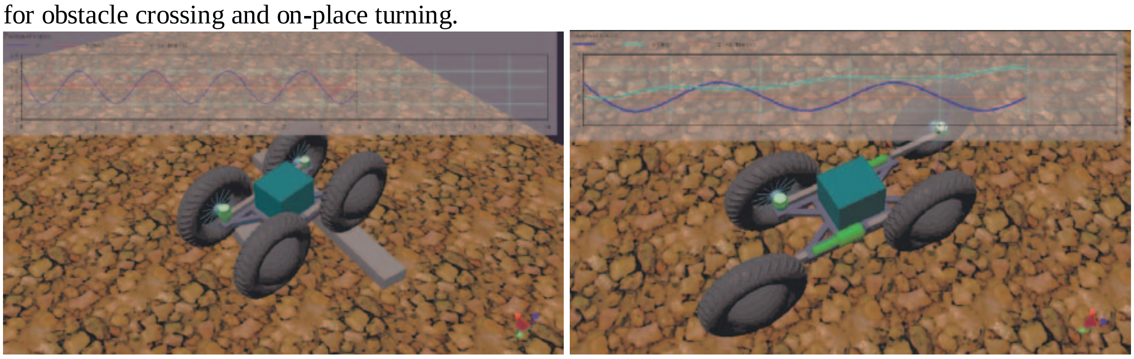


The wheels are used to protect the rover during landing. This is obtained by a special configuration of the wheels for landing.

The structure ,of the wheel is different from the concept N°1, with 13 radial chambers and a dedicated pneumatic system. Leakages and the compensation procedure have been studied.



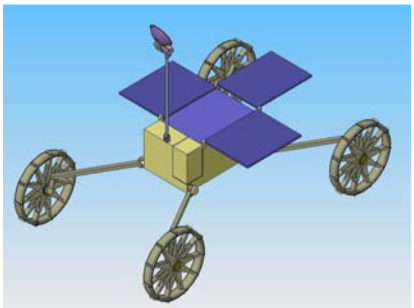
The progression of the rover using only the walking mechanism and the brakes has been studied by UIIP and simulated for obstacle crossing and on-place turning.



The rover configuration was rebuilt for the walking mode as presented in the figures and is referred to as concept N°4 in the technical report of the study. An experimental mock-up has been built and tested to verify the feasibility of this locomotion mode.

Concept 3 :

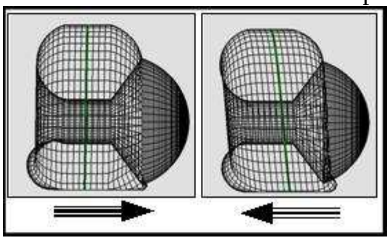
The third configuration is similar to the first one, adapted to unfolding wheels. In this case, the wheels cannot participate to the landing shock absorption. So, no reduction in the airbag system mass can be obtained.

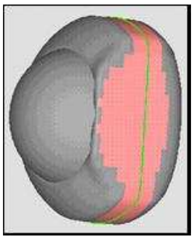


The 3 solutions have been compared in terms of mass, power and locomotion performances, and the results have been compared to Exomars rover ones.
The result is that the concept 1, with comparable mass of the lander, provides better locomotion performances and is thus considered as he more promising solution.

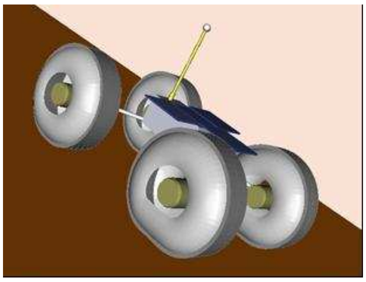
MODELLING ACTIVITIES

The inflatable wheels, the whole rover and the landing process have been modelled and simulated.
The wheel model was first used to analyse the lateral stability problem with the result illustrated in the following simulation result and also to compute the contact area with the soil to evaluate the traction characteristics.





This model was then simplified to a lighter one that allowed to simulate the whole rover, after verification of the simplification validity by comparison of both models. Simulation of the rover is illustrated here below.

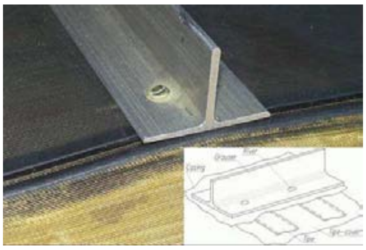


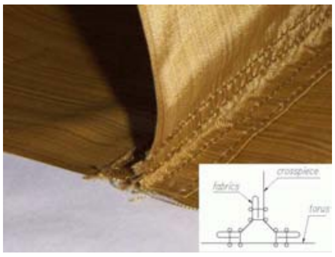
Landing Simulation :

The landing phase with both vented and non-vented airbags has been modelled and the pressure in the chambers simulated, as well as the acceleration levels. The limit of 70g as the specified maximum value can be preserved with the selected wheel diameter and with the additional airbag.

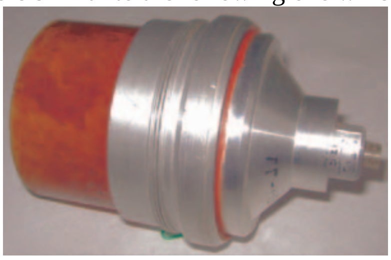
WHEEL TECHNOLOGY :

The manufacturing technology has also been studied
The materials were selected from earlier experience of Lavoshkin Association and the assembling process studied and prototyped as shown on the grouser and chamber division assembly procedure :

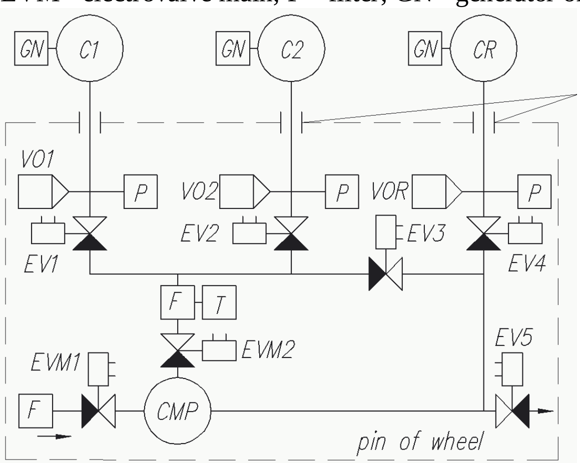


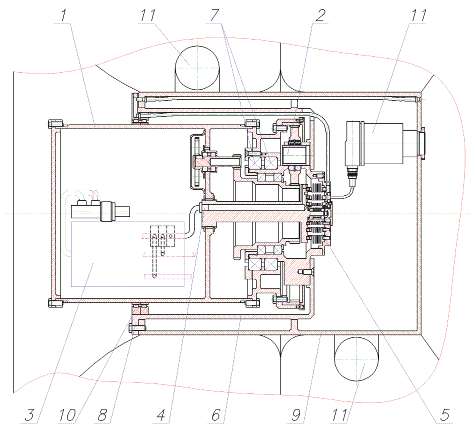


The wheels are inflated using gas generators similar to the following one which provides Nitrogen:

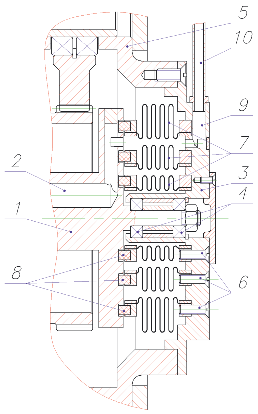


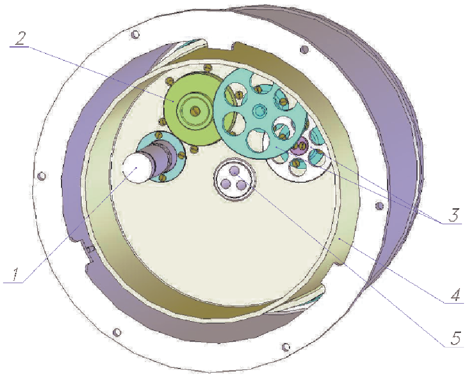
The pneumatic system is rather complex and able to regulate the pressure in the two wheel chambers as well as in the lateral one which operates at a higher pressure to rigidize the wheel and is also used as a tank to adjust the wheel chambers. A schematic diagram of the pneumatic system , is presented with the following abbreviations : T - temperature gauge; P - gauge of pressure; C – chamber; CMP – compressor; R - receiver
EVM - electrovalve main; F – filter; GN - generator of nitrogen; VO - verifying opening



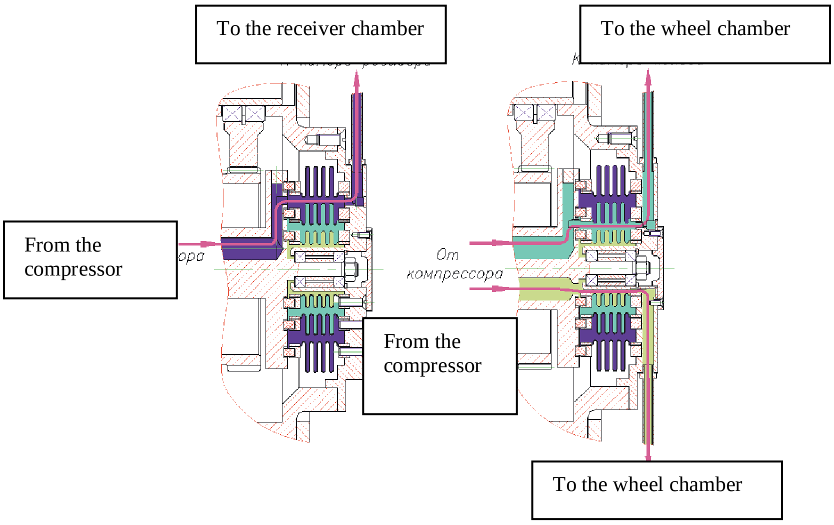


The mechanical architecture and particularly the implementation of the motors, gearboxes, pneumatic components, and sealing for rotating parts were analysed in detail.
The partial CAD views shows examples of the sealing implementation, of mechanical arrangement, and of the gas flow path.





1–motor; 2–brake; 3–row gears; 4–drive body; 5–pipeline canals 5



EVALUATION OF RESULTS :

The main characteristics of the different concepts are summarised in the following table that also refers to the Exomars reference one.

Locomotion system characteristics		Locomotion system version				
		VNIITransmash			UIIP	Exo-Mars concept E
		Concept 1	Concept 2	Concept 3	Concept 4	Concept E
Mass, kg	Landing module (lander)	340	350	380	380	340
	Shock-absorber system	10	-	140	140	140
	Rover	330	350	240	240	200
	Locomotion system	190	210	100	100	60
	Payload	140	140	140	140	140
Landing overload, g		70	TBD	120	120	120
Transport-position volume, m		1,45x1,2 x0,6	1,3x1,2 x1,2	1,2x1,2 x0,6	1.2x1.2 x1.2	1,2x1,2 x0,4
Wheel arrangement*		4x4x4x4	4x4x0x0	4x4x0x4	4x0x0x4	6x6x4x6
Mode of motion		wheeled, wheel-walking	wheeled, wheel-walking	wheeled, wheel-walking	wheel-walking (passive wheels)	wheel, wheel-walking
Method of turning		Side (as tractor), kinematic	Side (as tractor)	Side (as tractor), kinematic	Side (as tractor)	Side (as tractor), kinematic
Maximum speed of motion, m/s		0,028	0,028	0,028	0,016 (0,078)	0,028
Wheel type		inflatable, flexible	inflatable, flexible	unfolding, rigid	inflatable, flexible	rigid
Wheel diameter of grousers, m		1,36	2,06	0,8	1,36	0,35
Wheel width	Wheel	0,87	1,22	0,1	0,7	0,1

	of the running tread	0,3	0,3	0,08	0,2	
Wheel base, m		1,4…2,57	1,4…2,3	0,9…2,56	1,61…2,11	1,16…1,4
Wheel track, m		1,7	2,1	1,8	1	0,9
Clearance, m		0…1,45	0,2…1,8	0…1,2	0…1	0…0,37
Height of center of mass, m		0,5…1,5	0,7…1,5	0,54…1	0,25…1,25	0,2…0,45
Type of a wheel suspension		adaptive	rigid	adaptive	adaptive	balance
[illegible]	wheel	4	4	4	-	6

CONCLUSION

The study was organized to provide a comparison of inflatable wheels and unfolding wheels rovers with the Exomars rover as defined in phase A of the project, using the same main constraints. The analysis of the study results lead to the following conclusions :

Inflatable and unfolding wheels are suited for intermediate or large size rovers because of the additional equipments required, that have a negative impact on small rovers. The Exomars rover size lies in the middle range rovers and thus is a good comparison element.

With the technical solutions used in the study, inflatable wheels have better performances than the unfolding ones. However, this conclusion is not definitive and new concepts as the ones developed at LRP can still get the advantage with different mission requirements.

Both inflatable and unfolding wheels provide a substantial increase in cross-country ability of the rover. This is particularly important for loose soils terrains.

The inflatable wheels can participate to the landing shock damping, and in this case provide a better overall mass and performances budget than rigid wheels. The preferred solution was a hybrid use of wheels and dedicated vented airbag.

The inflatable envelope can be jettisoned in case of definitive failure, providing a secondary locomotion mode with the drawback of a slower progression speed of the rover.

Multi-chamber design solves the problems of stability of the rover on the non-rigid inflatable wheels, and provides a better reliability of the concept.

Ground clearance and payload attitude and height can be adapted in a very large range

The analysis of pure wheel-walking modes have shown that locomotion is possible even in case of total loss of the wheel power. This is at the expense of trajectory control which was not studied in this case.

Mathematical modeling for inflatable wheel and for landing shock have been developed. They can be used in breadboarding activities for performances evaluation.

The technological aspects require further investigation. The technical steps that have been proposed consist in

- developing an inflatable wheel and testing on several soils to verify the predicted behavior of wheel to soil contacts
- building a locomotion chassis to check the cross-country performances.