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Chassis Concepts for the ExoMars Rover

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INTRODUCTION

Following support provided to the European Space Agency (ESA) in 2002, for the in-house work on the Pre-Phase A activities of the ExoMars Mission of the Aurora Exploration Programme, RCL was contracted by ESA in summer 2003 to provide technical engineering support, consisting of engineering solutions and analysis as well as expert consultancy work, on rover locomotion aspects and rover chassis design, in the frame of the industrial Phase A activities of the ExoMars Rover. In this activity, called "Engineering Support on Rover Locomotion for ExoMars Rover Phase A", abbreviated ESROL-A, a number of chassis (i.e. locomotion subsystem) concepts were proposed and considered at the initial phases of concept selection. As a result of comparative analysis, a preferred concept of a locomotion subsystem was recommended. Several variants and design options for this concept were proposed.

THE INITIAL ROVER CHASSIS CONCEPTS

The three initial locomotion concepts named A, B and C were presented to ESA/ESTEC in July 2002 during two meetings in the frame of the "ExoMars09" Concurrent Design Facility (CDF) Pre-Phase A Study [1], from which concept Option C (then called concept 3) resulted as the recommended one. All three concepts have a passive rigid suspension (i.e. the linkages on which the wheels with their actuators are mounted in order to keep the wheel loads well distributed on uneven terrain do not contain any motors or flexible elements like springs) and the wheels themselves are rigid too.

- Option A: Locomotion concept with wheel formula 4x4x4
- Option B: Locomotion concept with wheel formula 4x4x4+4W
- Option C: Locomotion concept with wheel formula 6x6x4+4W

The "wheel formula" or "arrangement", by extrapolation of the terminology used for terrestrial off-road ground vehicles, is defined as: (total number of wheels) x (number of powered wheels) x (number of steerable wheels). The addition "+4W" indicates the additional presence of walking capability on the number of wheels indicated (i.e. 4 in all 3 cases here).
A general view and estimated main parameters and performance of the proposed concepts are given in Fig.1.

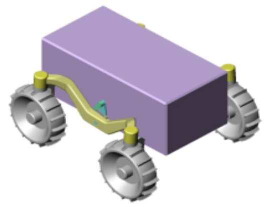
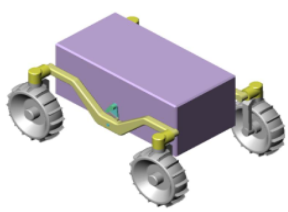
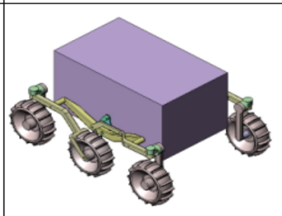
	Option A	Option B	Option C
Locomotion formula	4x4x4	4x4x4+4W	6x6x4+4W
Chassis Main Parameters			
Rover total mass (incl. 20% margin), kg	240	240	240
Chassis mass (incl 10% margin), kg	55	68,75	76,78
Wheel diameter, м	0,4	0,4	0,35
Wheel track, м	1	1	1
Wheel base, м	0,7	0,7…1,3	0,8…1,4
Clearance, м	0,28	0,28	0,28
Surmountable step, м	0,15	0,15	0,3
Surmountable sandy slope,degr.	15	22	25

Fig.1 Initial chassis concepts A,B and C proposed during ESA's "ExoMars09" Pre-Phase A CDF study

In the illustrations of our work the rover's payload and service equipment are represented by a simple rectangular box. The proposed concepts and dimensions were based on requirements provided by ESA, including step-climbing capability of 0.3 m and uphill gradeability (slope climbing capability) on loose sandy terrain of 25 degrees. As indicated in the table, with the dimensions considered based on volume constraints inside the Descent Module (DM) that delivers the Rover to the Martian surface, only the six-wheeled configuration was (and is) expected to fully meet these requirements.

CONCEPT A

Different configurations of concept A when moving and maneuvering are shown in Fig.2. The wheels of each board (i.e. each lateral side of the rover) are installed in pairs on the longitudinal levers or yokes connected with each other by means of an averaging linkage (synchronizing mechanism), which provides rotation of the levers w.r.t. the rover body at identical angle in opposite directions, as shown in (b). Due to the symmetry of the operation of this passive transmission so-called Body Posture Averaging is achieved in the longitudinal direction. All wheels are provided with individual steering drives. The chassis longitudinal dimension in stowed configuration (1.2 m) limits (for reasons of accommodation inside the DM) the wheel diameter D to the value of about 0.6 m that allows to estimate the maximum height of a surmountable obstacle at 0.24 m (0.4 D), which is still less than the value of 0.3 m specified by ESA. Uphill gradeability on sandy slopes is estimated at 15^o, which is also less than the required value (25 deg.). The concept A needs to be stowed in one of the shown configurations, e.g. (a) or (d) in Fig.2, or specific one-way deployment mechanisms should be added.

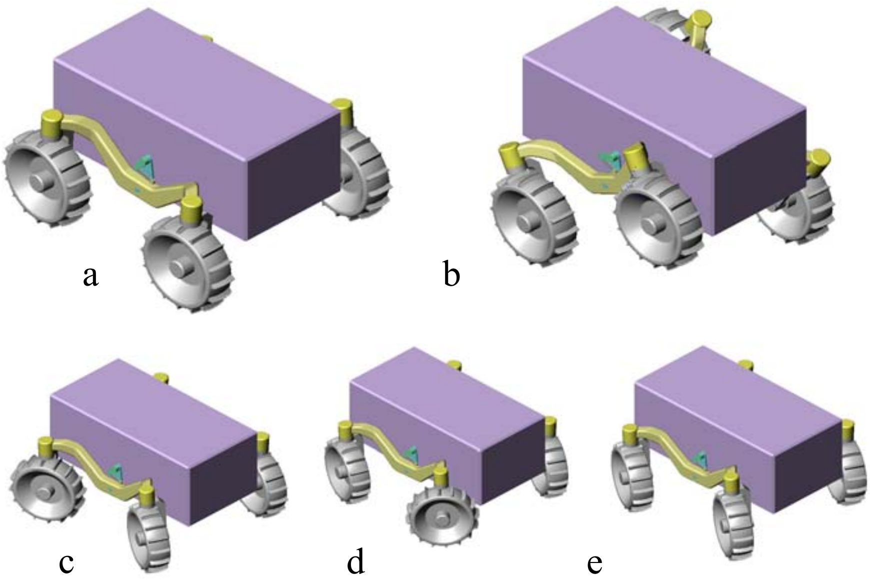


Fig.2 Chassis Concept A
a – general view; b – configuration while moving on rough terrain; c – turning on the move; d - turning in place; e – moving with angle to the chassis longitudinal axis

CONCEPT B

The difference between concepts A and B is that each of the wheels of Concept B is provided with a walking drive, which allows the wheel to perform a walking movement, i.e. the wheel can swivel forward and backwards which, if combined in a proper way with the action of the wheels's traction actuator and with proper synchronization of these 2 functions of all wheels, creates the walking function which significantly increases gradeability, as demonstrated in the past by the VNII Transmash "Marsokhod" designs. Various configurations of concept B are shown in Fig. 3. The utilization of the wheel-walking mode can allow such a rover to climb sandy slopes of up to 22°. Furthermore, theoretically, Concept B provides a possibility to negotiate higher obstacles than those of Concept A, in case of using an actively controlled obstacle negotiation whereby redistribution (equalization) of the wheel loads with the help of walking drives is performed in real-time while negotiating the obstacles. In practice, such a method requires an intelligent control system to fully supervise and govern the loads and positions of the wheels, as well as the 3-D position of the rover itself in order to keep its stability.

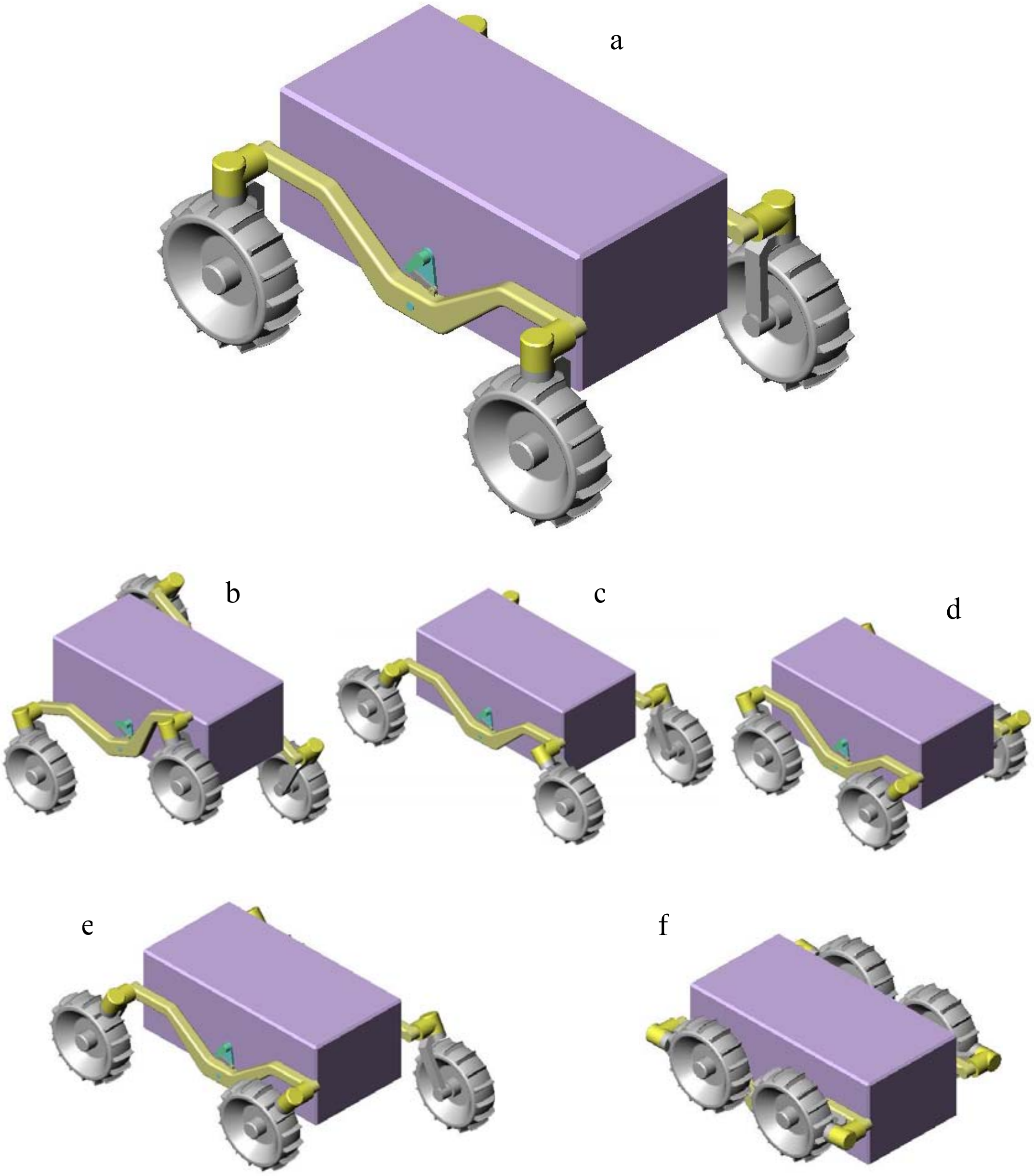


Fig. 3 Chassis Concept B
a – general view; b – configuration while moving on rough terrain; c – configuration with long wheelbase; d – configuration with short wheelbase; e – wheel-walking locomotion mode; f – stowed configuration

CONCEPT C

Concept C is shown in various configurations in Fig. 4. The wheels of one board are connected with each other and with the rover body by means of the suspension, formed by a hinge-lever mechanism. Kinematics of the latter provides equalization of the loads of the three wheels of one board for the nominal chassis configuration on even horizontal surface. Moreover, the two three-wheel board modules are additionally connected with each other by means of an averaging linkage (synchronizing mechanism, analogous to the ones used in options A and B).

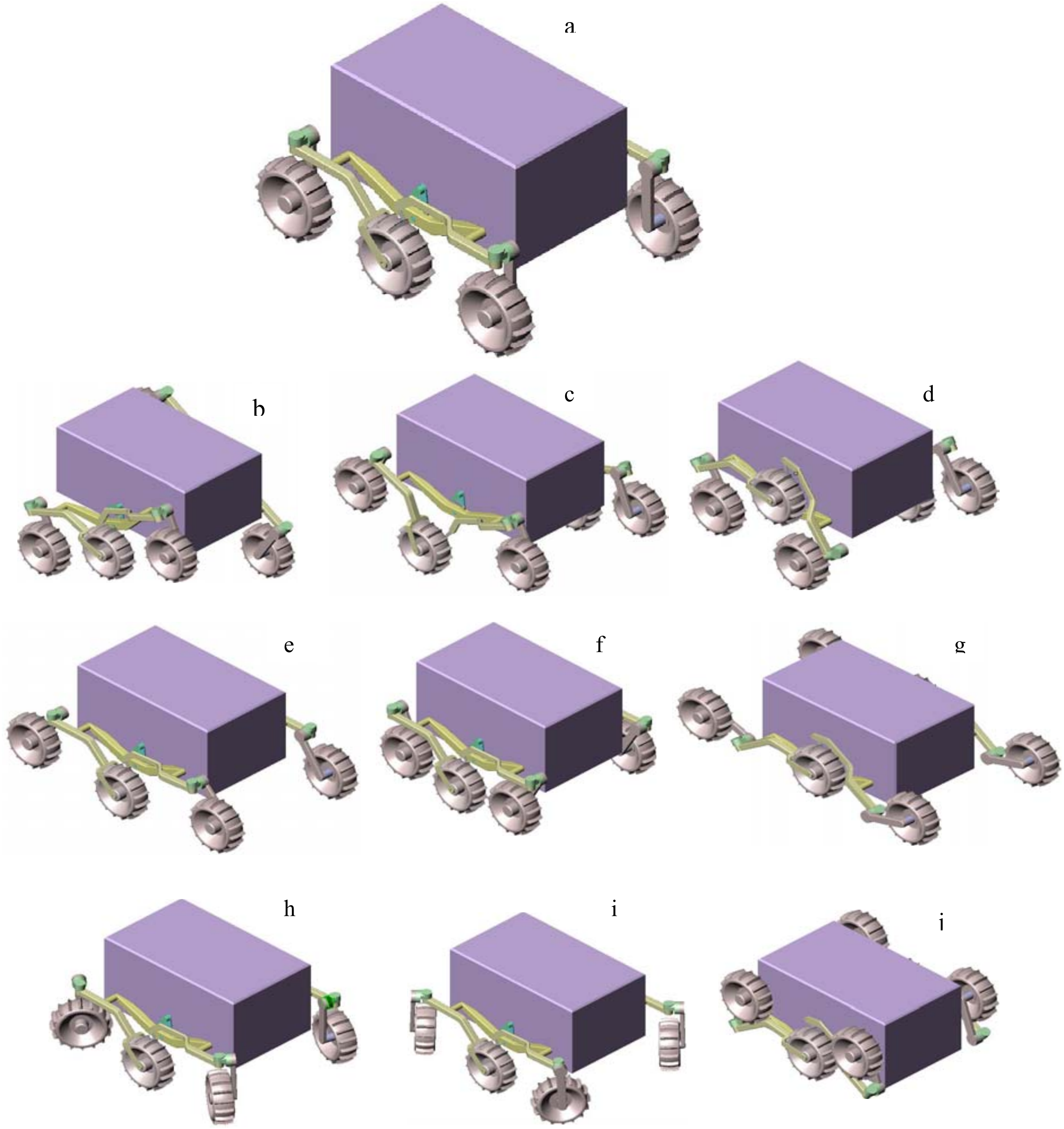


Fig.4. Chassis Concept C
a – general view; b,c,d –configuration while moving on rough terrain; e – configuration with long wheelbase; f – configuration with short wheelbase; g –configuration with rover body lowered to the ground; h – turning on the move; i – point turning ; j – stowed configuration

This mechanism constrains rotation of the central yoke of the boards to identical angles in opposite directions relative to the rover body. The four corner wheels are provided with individual steering drives for turning and walking drives for walking. Concept C ensures negotiation of steps of 0.3 m height and an uphill gradeability (in wheel-walking mode) on sandy slopes of 25°. Moreover, this locomotion concept provides a number of additional functions. First, when moving along a hillside (on a "crosshill path"), the rover can equalize the loads on its boards, using the walking drives (Fig.5), which is necessary for approaching as much as possible an equalization of the loads on the wheels. The (passive) hinges of the chassis articulation can be equipped with angular position sensors. In this case information on the spatial position of the rover can be used to estimate its current stability status and predict subsequent motion events. Second, stowing of the locomotion subsystem into the transportation configuration and its deployment to the operational configuration is carried out (by analogy with concept option B) with the help of walking drives, which compensates for the additional mass of the walking function by reducing the need for specific deployment actuators. Moreover, during Mars surface operations, the rover can lower itself down to the soil using the walking drives (e.g. in order to perform scientific investigations), which could simplify the payload deployment mechanism design such as the positioning device of the drilling and sampling subsystem.

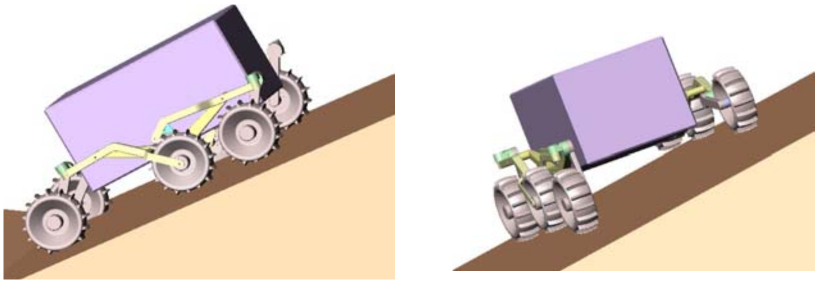


Fig. 5 Chassis Concept C wheel load redistribution on slopes

FURTHER DEVELOPMENT OF THE LOCOMOTION CONCEPTS

CONCEPT D

The main reason for further development of the initially selected concept C was the desire to enhance its trafficability (which is the one of the primary functions of the chassis) by improving the design of the suspension, which is the key chassis element that, together with the wheels, determines rover trafficability. However, unlike the number of wheels and their dimensions, which are more or less determined by soil trafficability and cannot be changed considerably within a specified containment volume, the suspension design, which significantly influences the obstacle-crossing capability, was at this point not yet settled to a commonly recognized optimal concept yet. Furthermore, the improvement of the design of the suspension, which is the largest part of the chassis, will affect other parameters of the chassis: mass, rigidity, power consumption, robustness and reliability.

The ideal non-flexible rocking lever suspension should ensure uniform loading of all wheels not only on an even surface but on a surface with complex relief too. Fig. 6 shows one of possible situations: a chassis with wheel formula 6x6 surmounts a bump from right to left. The bump is higher than 0.4 D and therefore the pair of rear wheels should negotiate a part of a vertical wall. The figure shows the terrain reaction forces perpendicular to the contact surfaces and the resulting traction forces based on a simple Coulomb friction model of the contact.
Assuming that: $P_{X1} + P_{X2} = P_{X3}$, and $P_{Xi} \leq \varphi_i P_{Zi}$, the condition of obstacle negotiation is $\varphi_3 (\varphi_1 P_{Z1} + \varphi_2 P_{Z2}) \geq P_{Z3}$, where φ is the adhesion coefficient. For a case when $\varphi_1 = \varphi_2 = \varphi_3$, and when the suspension kinematics provides equalization of the wheel loads ($P_{Z1} \approx P_{Z2} \approx P_{Z3}$) independent of the wheel displacement, then: $\varphi \geq 0{,}5^{0{,}5} \approx 0{,}7$.
This means, that negotiation of an obstacle on homogeneous hard soil provided with uniform loading of the wheels is possible if the adhesion (friction) coefficient of the wheel with soil is more than 0.7. However the suspension of concept option C and similar suspensions of other designs (like NASA/JPL's Rocker-Bogie and SOLERO or Shrimp of EPFL in Lausanne, Switzerland) do not completely equalize the wheel loads while moving over a rough terrain.

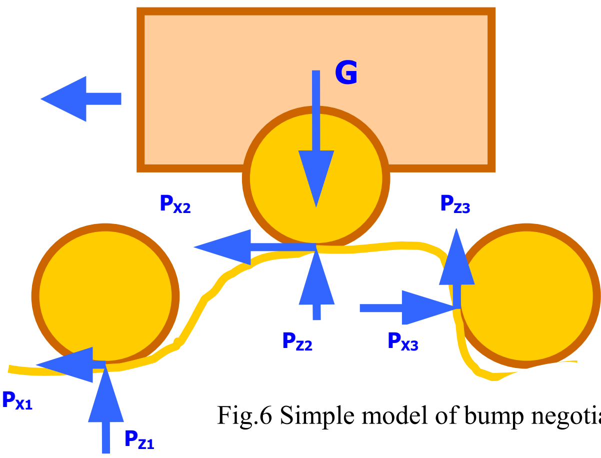


Fig.6 Simple model of bump negotiation

Thus, the rover obstacle trafficability (in real situation, where adhesion with soil/obstacles should be always taken in to account) depends essentially on features of its suspension. That is why the elimination of longitudinal displacement of wheels would enhance the rover's obstacle trafficability. This idea showed the direction for further development of the locomotion concept and, in particular, was used by RCL to develop the chassis of "ExoMaDeR" (i.e. ExoMars

Demonstration Rover) model designed and built for ESA's Automation and Robotics Section. We refer to the ExoMaDeR chassis concept as "Concept D". It is a six-wheel chassis with 6 powered wheels, the 4 corner ones of which are steerable. A general view of the ExoMaDeR model, which is a 1:2 scale model of the corresponding ExoMars chassis design, is shown in Fig.7. The wheels are individually equipped with wheel drives with digital encoders that are installed inside the wheels. The wheels are attached to the platform with the help of fork-shape brackets and multi-leverage suspension system. The wheels of each board are connected with each other and with the rover frame by means of a hinge-lever suspension. Kinematics of the latter provides rather accurate vertical displacement of all three wheels over their full displacement range. The two three-wheel board modules are additionally connected with each other by means of an averaging linkage (synchronizing mechanism), which provides rotation of these modules to identical angle in opposite directions relative to the platform on which service equipment and payload can be mounted.

Fig.7 ExoMaDeR model (Concept D) while negotiating rocks (ESTEC A&R Lab)

Tests performed at ESTEC's Automation and Robotics Laboratory testbed have shown that the chosen approach was right. The trafficability of the chassis with 5 kg load proved to be even higher than it was specified. The chassis with 5 kg load demonstrated the mobility parameters that were expected for the chassis only (without load). A drawback of Concept D, however, is the relative complexity of the suspension.

CONCEPT E

Based of the experience acquired during the development and tests with the ExoMaDeR model, a simpler version of a concept of the locomotion system with wheel load equalizing suspension was proposed. This new concept E was named "three-module concept". Whereas Concepts C and D have two suspension modules with three wheels each Concept E utilizes three independent suspension modules with two wheels each (Fig.8).

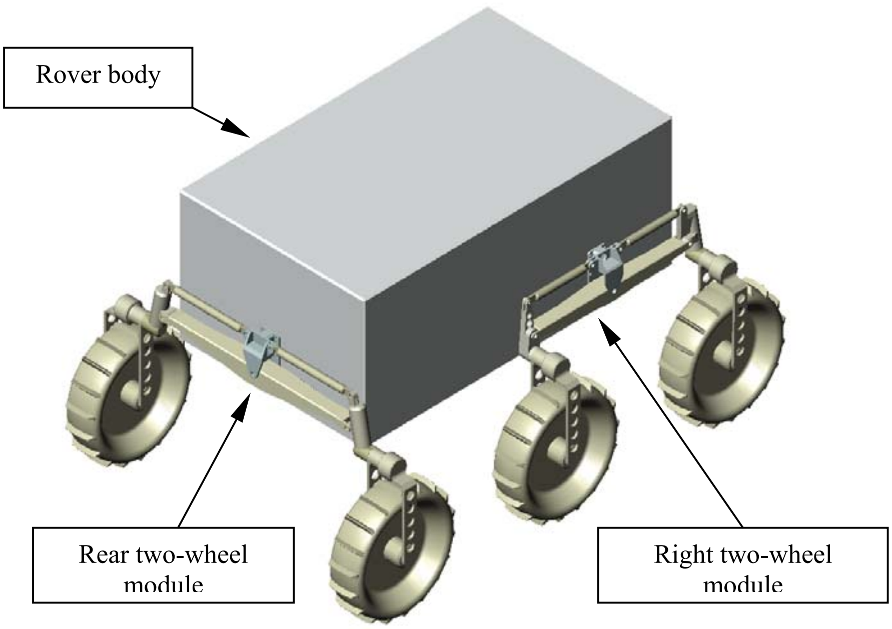


Fig. 8 Concept E

During movement on a surface with complex relief, the suspension ensures contact of all wheels with the soil and their uniform loading in a passive way without any averaging linkage. The design of the module linkages are such that the wheel-soil contact points move up and down nearly vertically w.r.t. the rover body. Fig.9 shows various configurations of Concept E when moving over rough terrain.

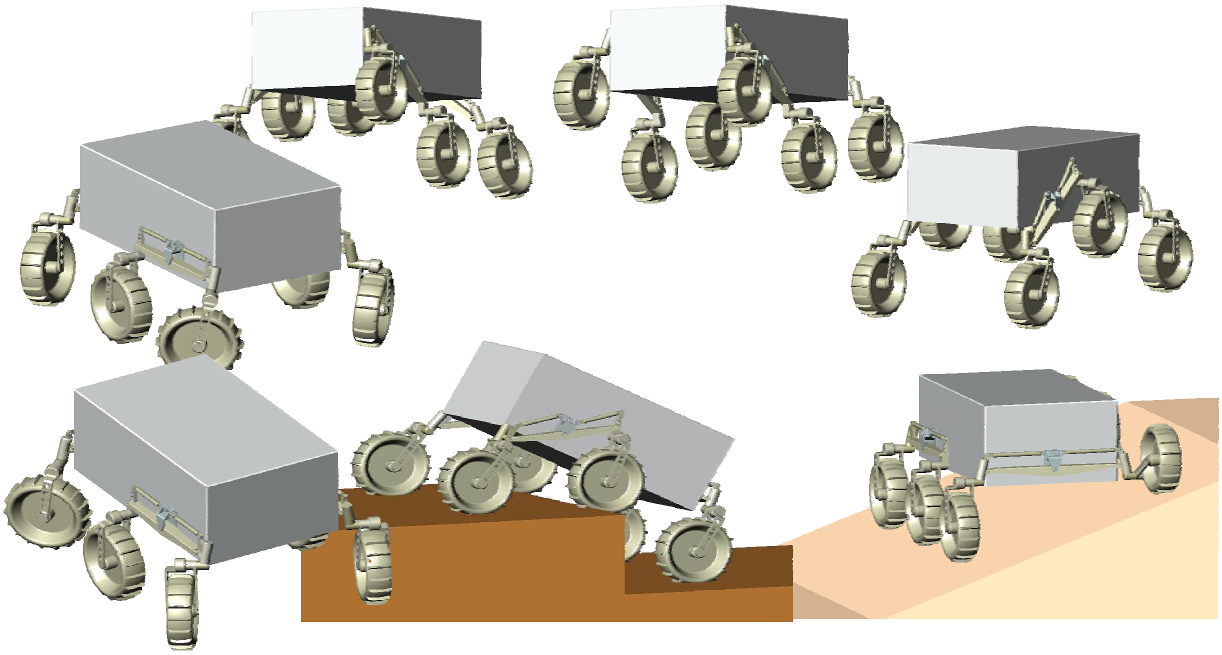


Fig.9 Concept E on obstacles

The stowed configuration of the rover locomotion subsystem in a Descent Module internal volume with the shape of a parallelepiped, is given in Fig.10. Stowed configuration is realized with the help of the walking mechanisms, which rotate the wheels to (180-210)° w.r.t. their nominal operational positions.

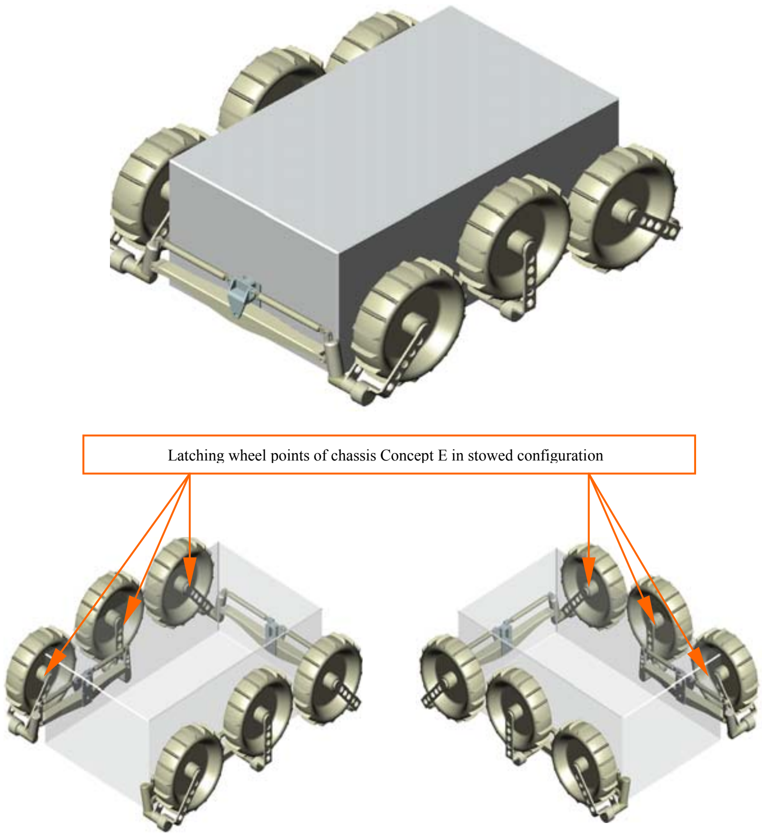


Fig. 10 Stowed configuration of Concept E in Descent Module of parallelepiped shape

The Descent Module internal volume shape obviously affects the rover locomotion subsystem complexity and mobility performance. That is why alternative stowed configurations of the Concept E for different shapes of the Descent Module were proposed and analyzed (Fig.11).

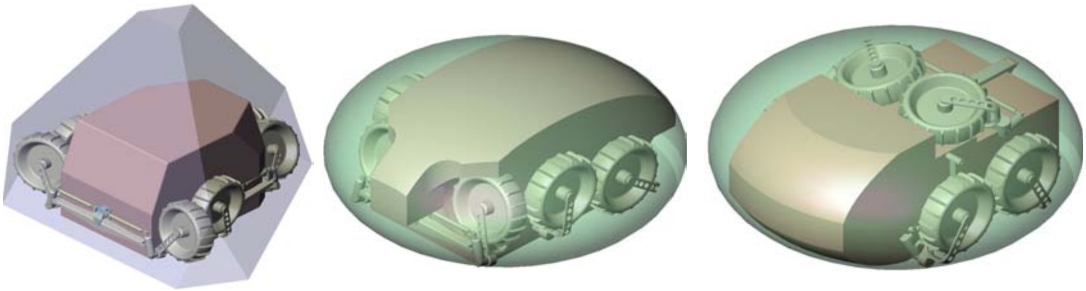


Fig.11. Stowed configurations of Concept E variants in Descent Modules of different shape

In order to propose design solutions and validate the preliminary estimated mass of the chassis concept E, some more detailed design activities were undertaken. A preliminary design was performed, using 3D CAD tools, of a breadboard model based on concept option E. Such a chassis breadboard model should allow representative demonstration of the mobility performances of the ExoMars Rover in Earth condition. Another objective was to attempt to design the breadboard chassis model within the mass allocation of the ExoMars rover flight chassis. This would prove that the proposed ExoMars chassis mass of 58.4 kg is feasible for a 200 kg rover. Fig. 12 shows a general view of this chassis breadboard design.

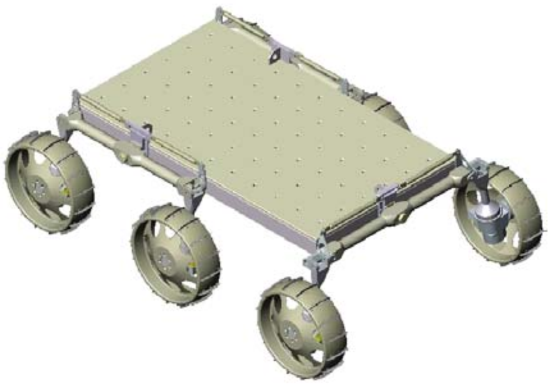


Fig.12 General view of the breadboard chassis model based on Concept E

The results of the first phase of chassis breadboard model design confirm the possibility to develop a chassis with the required performance. During the preliminary design of the chassis breadboard model we found that it was possible to even increase certain characteristics w.r.t. the requirements. The total mass of the chassis breadboard model designed in 3D CAD is approximately 60 kg for the option with maximum number of drives (6x6x6x6W) and with a platform for service equipment and payload. The preliminary estimated mass of ExoMars Rover chassis was 58.4 kg (for the drive option 6x6x4x4W and without service equipment/payload platform).

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